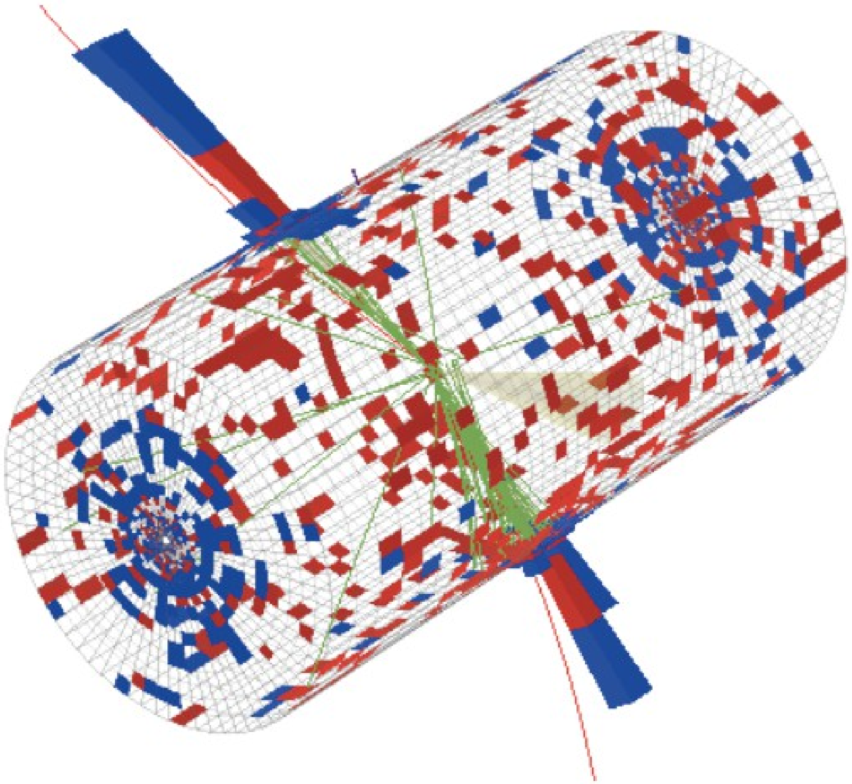
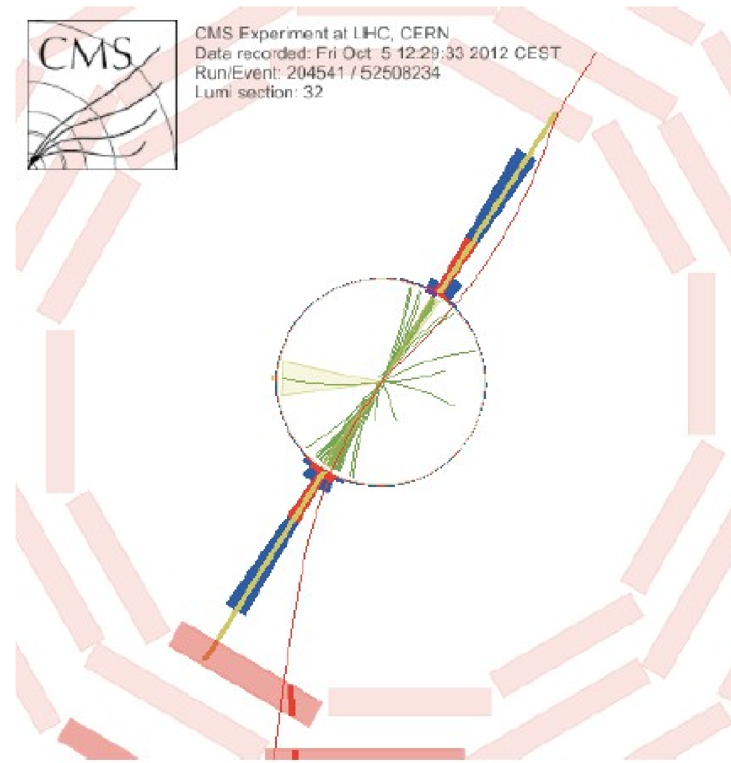
Distinguishing dijet resonances at the LHC





Based on:
R. S. Chivukula, E. H. Simmons, NV
Phys.Rev. D91 (2015) 5, 055019

Natascia Vignaroli

Michigan State University

Fermilab, 23th April 2015

Outline

Dijet channel: simple and powerful probe of many different scenarios of new physics at the LHC

Anticipating the discovery of a new dijet resonance at the 14 TeV LHC, can we distinguish if it is a quark-antiquark, a quark-gluon, or a gluon-gluon resonance?

- Color-discriminant variable

Atre *et al* Phys. Rev. D 88, 055021 (2013)

$$D_{col} = \frac{\sigma_{jj} M^3}{\Gamma}$$

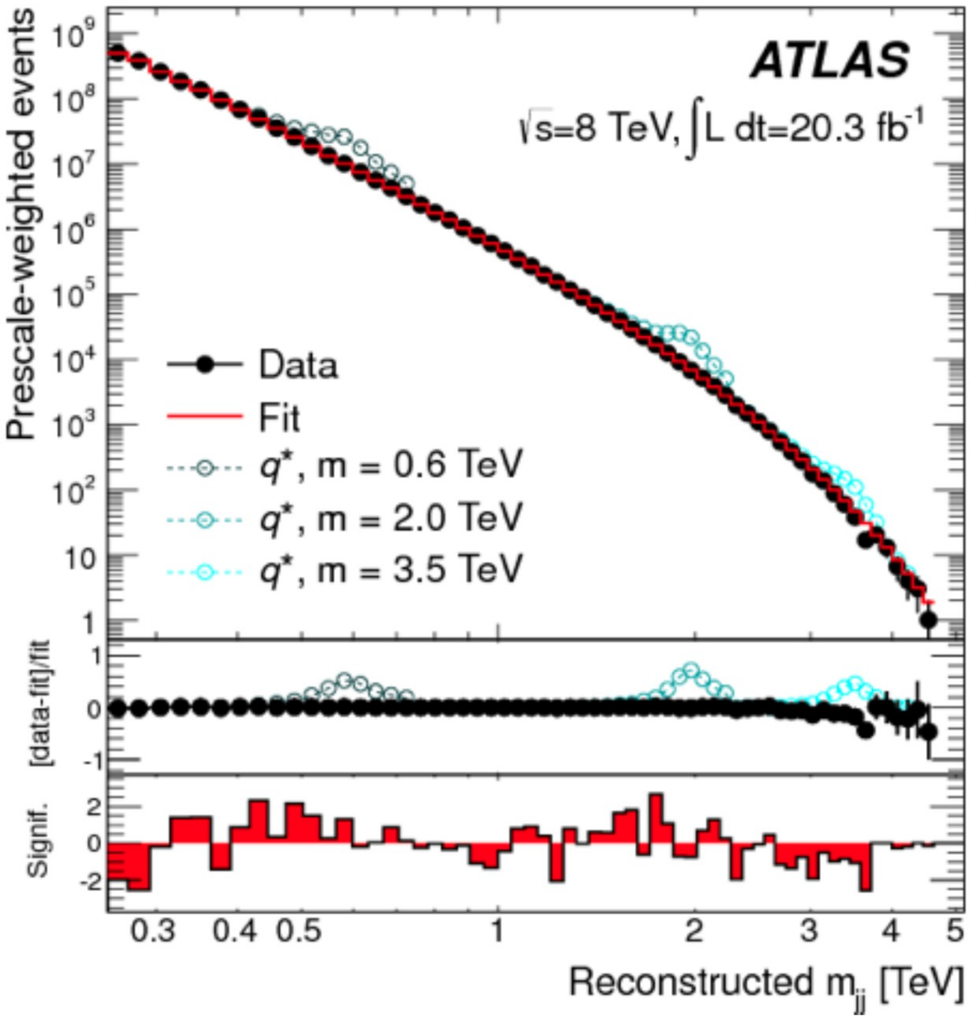
(statistical+systematic effects included)

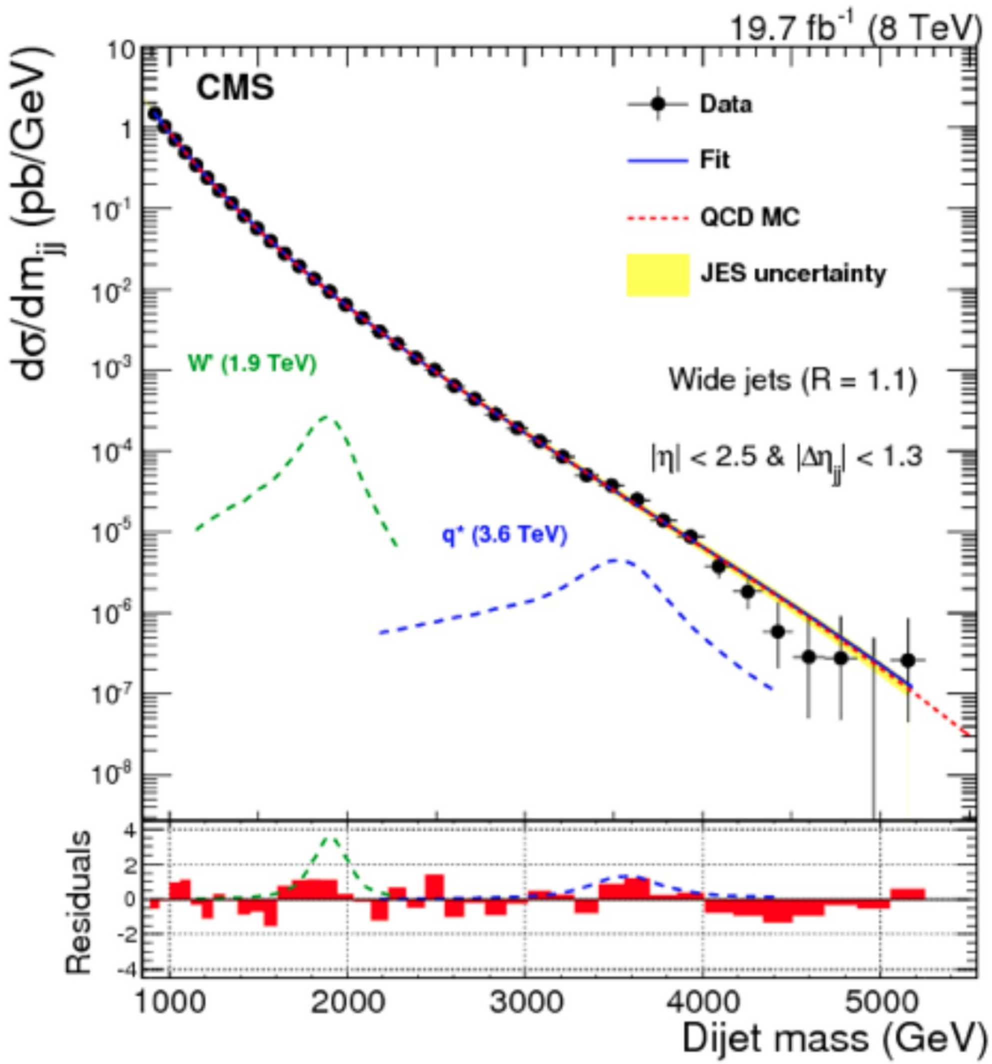
- Study of the jet energy profile

  [model-independent]

(Only statistical analysis)

LHC dijet data



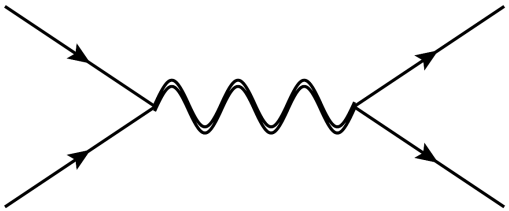


ATLAS, arxiv:1407.1376

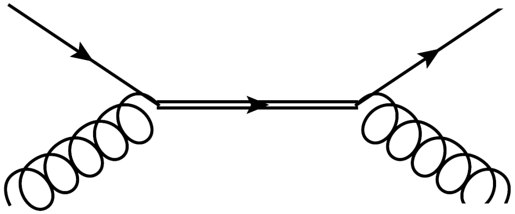
CMS, arxiv:1501.04198

Benchmark models for dijet resonances

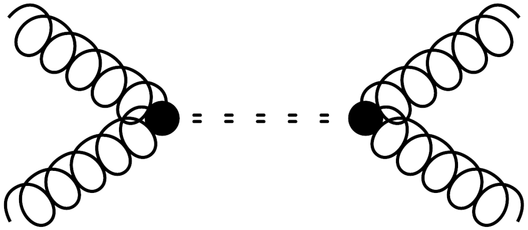
- Flavor universal coloron (quark-antiquark)



- Excited quark (quark-gluon)



- Color-octet scalar (gluon-gluon)



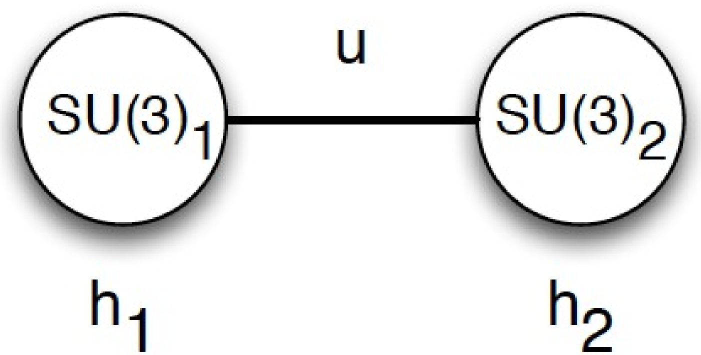
We will analyze the possibility to distinguish these three types of resonances in the mass-coupling parameter space, not excluded by LHC-8, and where a 5 sigma discovery can be reached at the 14 TeV LHC

quark-antiquark

Quark-antiquark resonances are present in many different kinds of new physics scenarios.
Examples: Color-singlet vector bosons Z' and W', color-octet vector bosons (coming from extra-dimensional theories or from models with new strongly-interacting dynamics)

Flavor Universal Coloron Model

Chivukula, Cohen, Simmons '96, PLB 380, 92



$$SU(3)_1 \times SU(3)_2 \to SU(3)_{QCD}$$

$\Rightarrow \begin{cases} \text{Massless } \textbf{SM gluon} \\ \text{Massive color-ocet vector boson } (\textbf{Coloron}) \end{cases}$

$$\tan\theta = \frac{g_2}{g_1} \qquad g_S = g_1 \sin\theta = g_2 \cos\theta \qquad m_C = \frac{g_S u}{\sin\theta\cos\theta}$$

Coloron interactions:

$$-\underline{g_S \tan\theta} \sum_f \bar{q}_f \gamma^\mu \frac{\lambda^a}{2} q_f C^a_\mu$$

FU coloron is *produced* by quark-antiquark annihilation
and *decay* to quark-antiquark

$$\Gamma(C) = \alpha_S m_C \underline{\tan^2\theta}$$

CMS has considered this FU COLORON model as a benchmark, fixing tanθ=1

quark-gluon

Quark-gluon resonances could appear in

- composite models as excited quarks — Baur, Spira, Zerwas '90; Baur, Hincliffe, Zeppenfeld '87
- composite Higgs models with specific flavor structures — M. Redi et al JHEP 1308, 008 (2013)

We consider the phenomenological model of [Baur, Spira, Zerwas, PRD 42, 815 (1990)] which describes an electroweak doublet of excited color-triplet vector-like quarks **q*=(u*, d*)** coupled to first-generation ordinary quarks:

$$\mathcal{L}_{int} = \frac{1}{2\Lambda}\bar{q}^*_R\sigma^{\mu\nu}\left[g_S \underline{f_S} \frac{\lambda^a}{2} G^a_{\mu\nu} + g f \frac{\tau}{2}\cdot \mathbf{W}_{\mu\nu} + g^{'} f^{'} \frac{Y}{2} B_{\mu\nu}\right] q_L + \mathrm{H.c.}$$

We take (as in ATLAS, CMS) $\Lambda = m_{q^*}$ $\quad \underline{f_S} = f = f'$

$$\Gamma(q^* \to qg) = \frac{1}{3}\alpha_S \underline{f_S^2} \frac{m^3_{q*}}{\Lambda^2}$$

BR[q* → qg] ≈ 80 %

gluon-gluon

A gluon-gluon final state can generally arise from decay of colored scalars in models with extended color gauge structures

Frampton, Glashow '87; Hill '91;
Martynov, Smirnov '09; Bai, Dobrescu '11;
Chivukula, Simmons, NV '13

We adopt the effective description by [Han, Lewis, Liu, JHEP 1012, 085 (2010)]

$$\mathcal{L}_{S_8} = g_S d^{ABC} \frac{k_S}{\Lambda_S} S_8^A G^B_{\mu\nu} G^{C,\mu\nu}$$

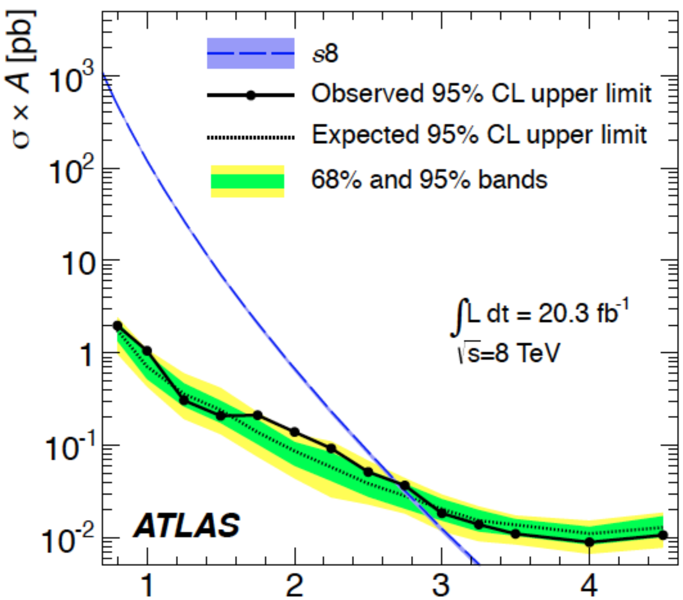
Color-octet scalar S_8 is produced by gluon fusion and completely decays into gg

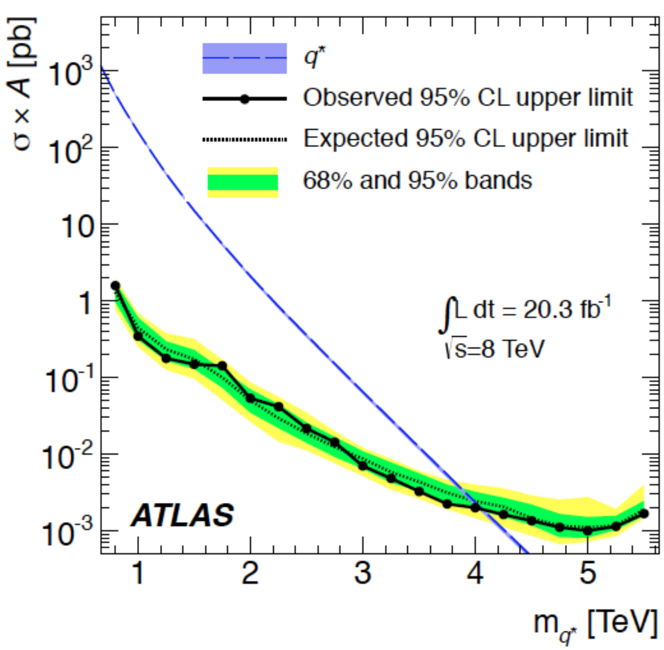
$$\Gamma(S_8) = \frac{5}{3} \alpha_S \frac{k_S^2}{\Lambda_S^2} m_{S_8}^3$$

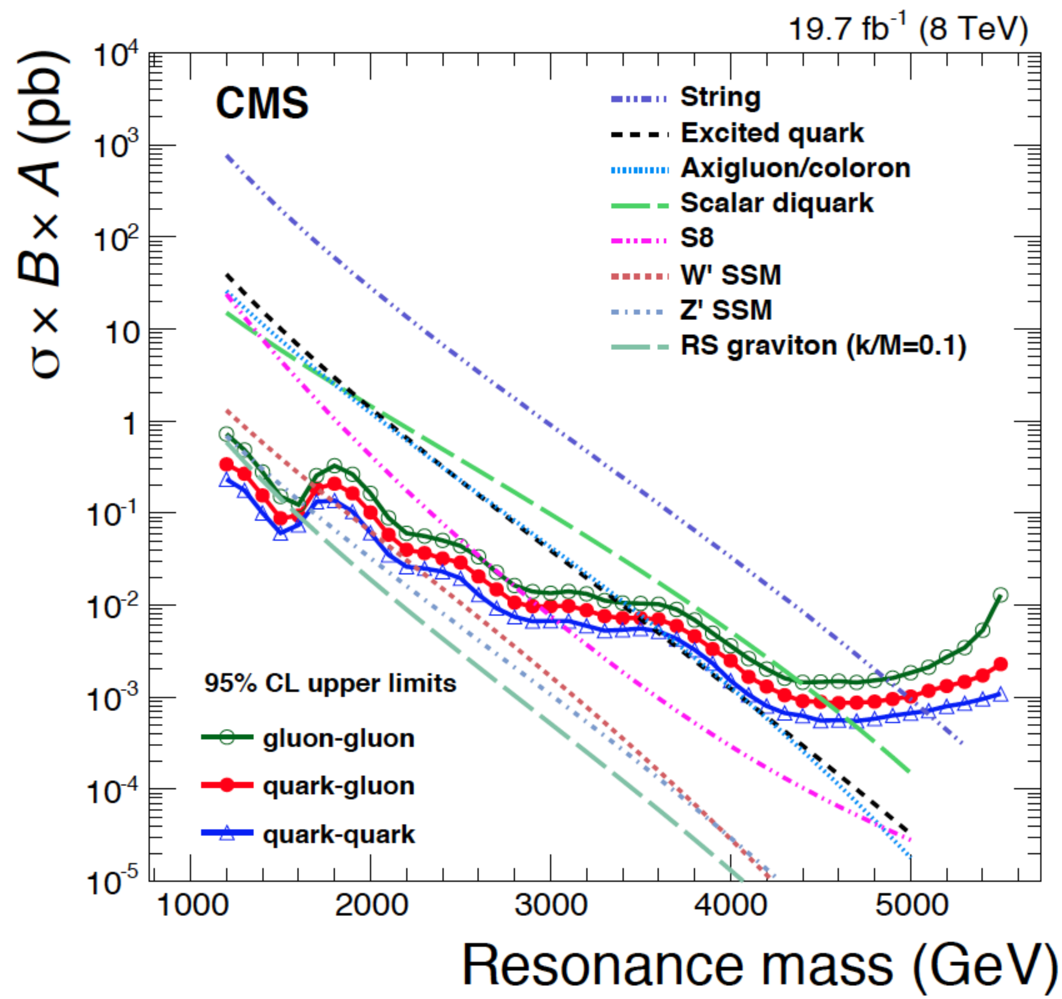
As considered by ATLAS, CMS we take $\Lambda_S = m_{S_8}$

LHC-8 Exclusion

CMS arXiv:1501.04198
ATLAS arXiv:1407.1376







LHC-14 Discovery Reach

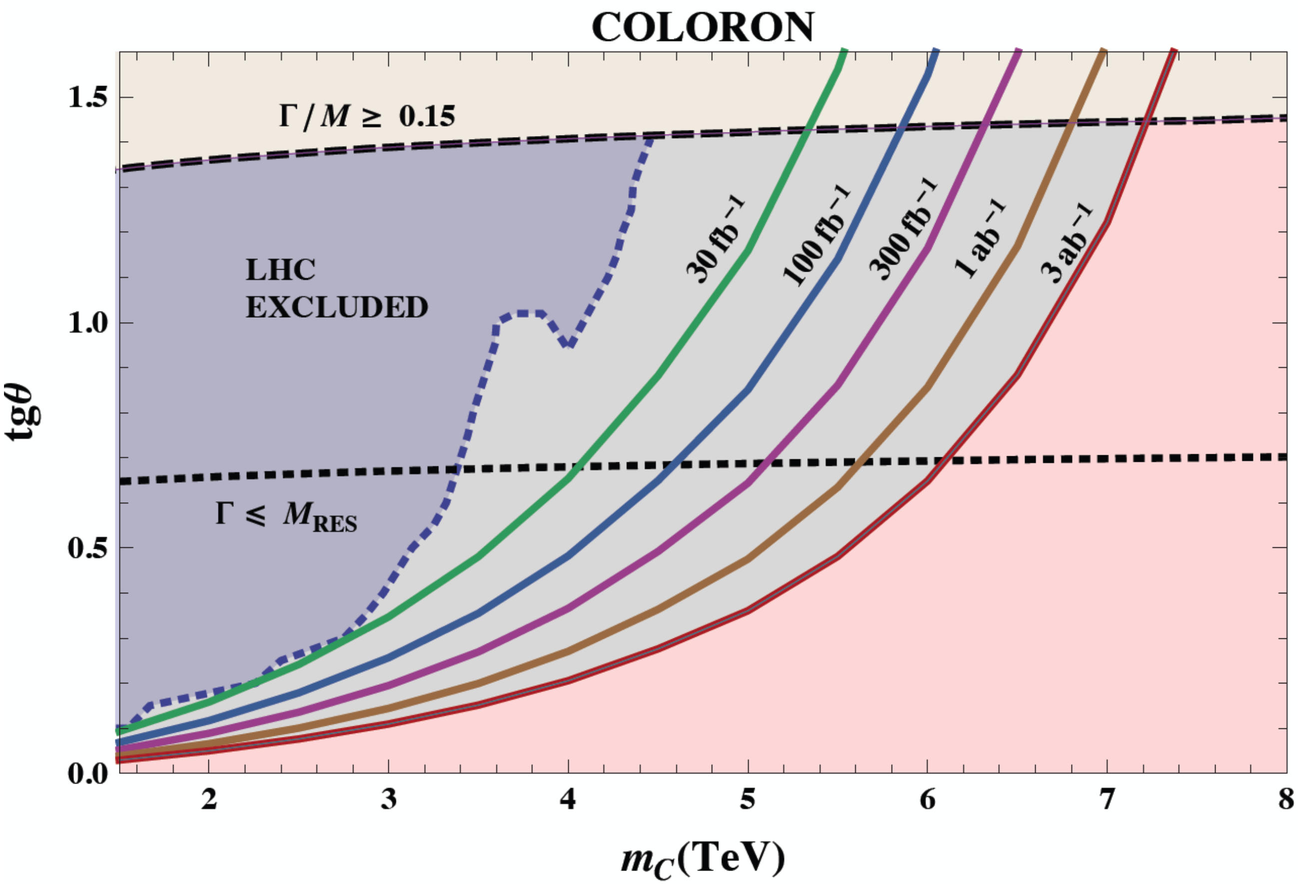
MC simulation (MG5+Pythia)

Inspired by CMS cuts, arXiv:1501.04198

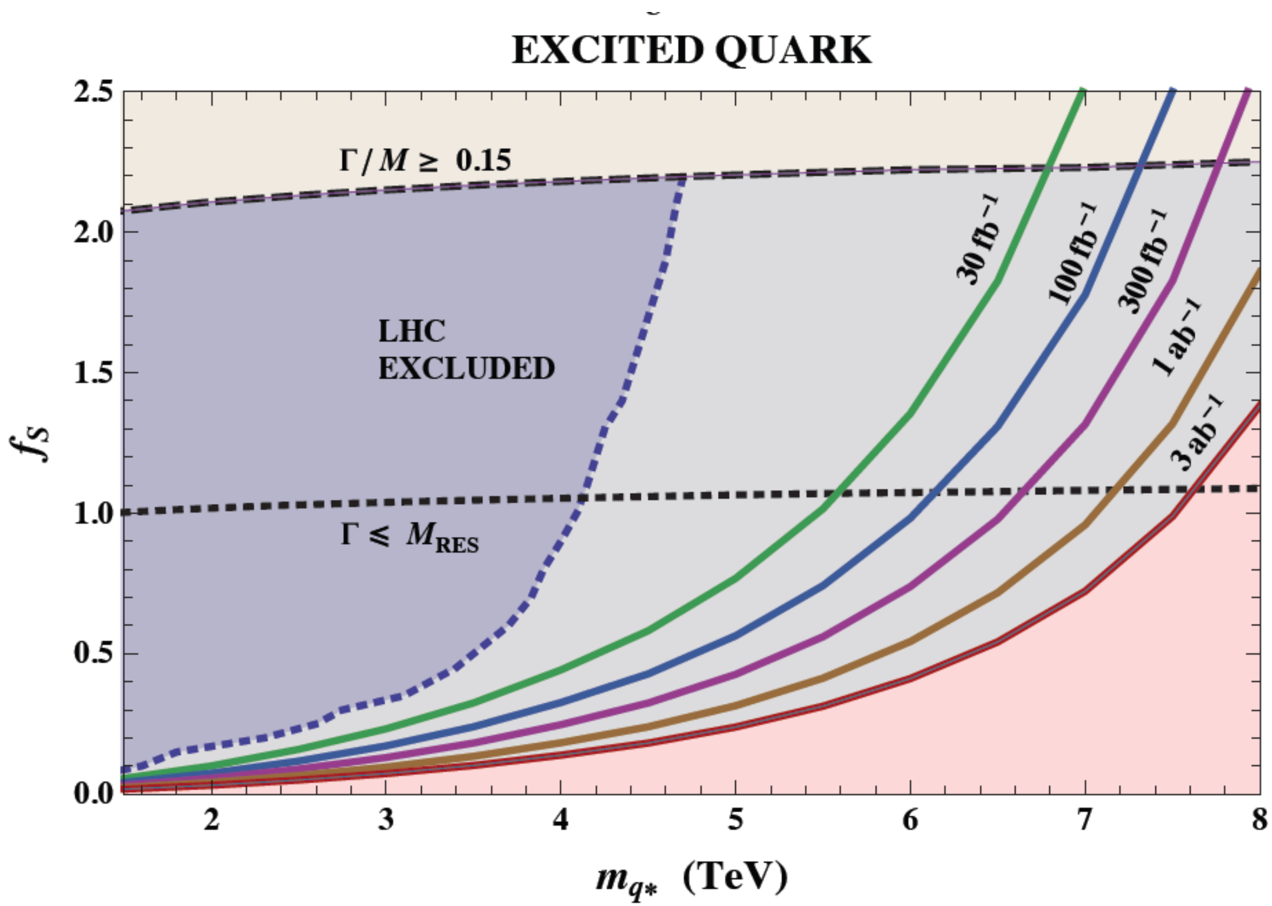
jets reconstructed with Fastjet, anti-kt R=0.5

- pT> 30 GeV, $|\eta| < 2.5$
- t-channel rejection: $|\Delta\eta| < 1.3$
- Dijet mass in [0.85 M, 1.15 M]
- Acceptance rates: 50% - 60% for benchmark models
- QCD dijet background extracted from arXiv:1308.1077

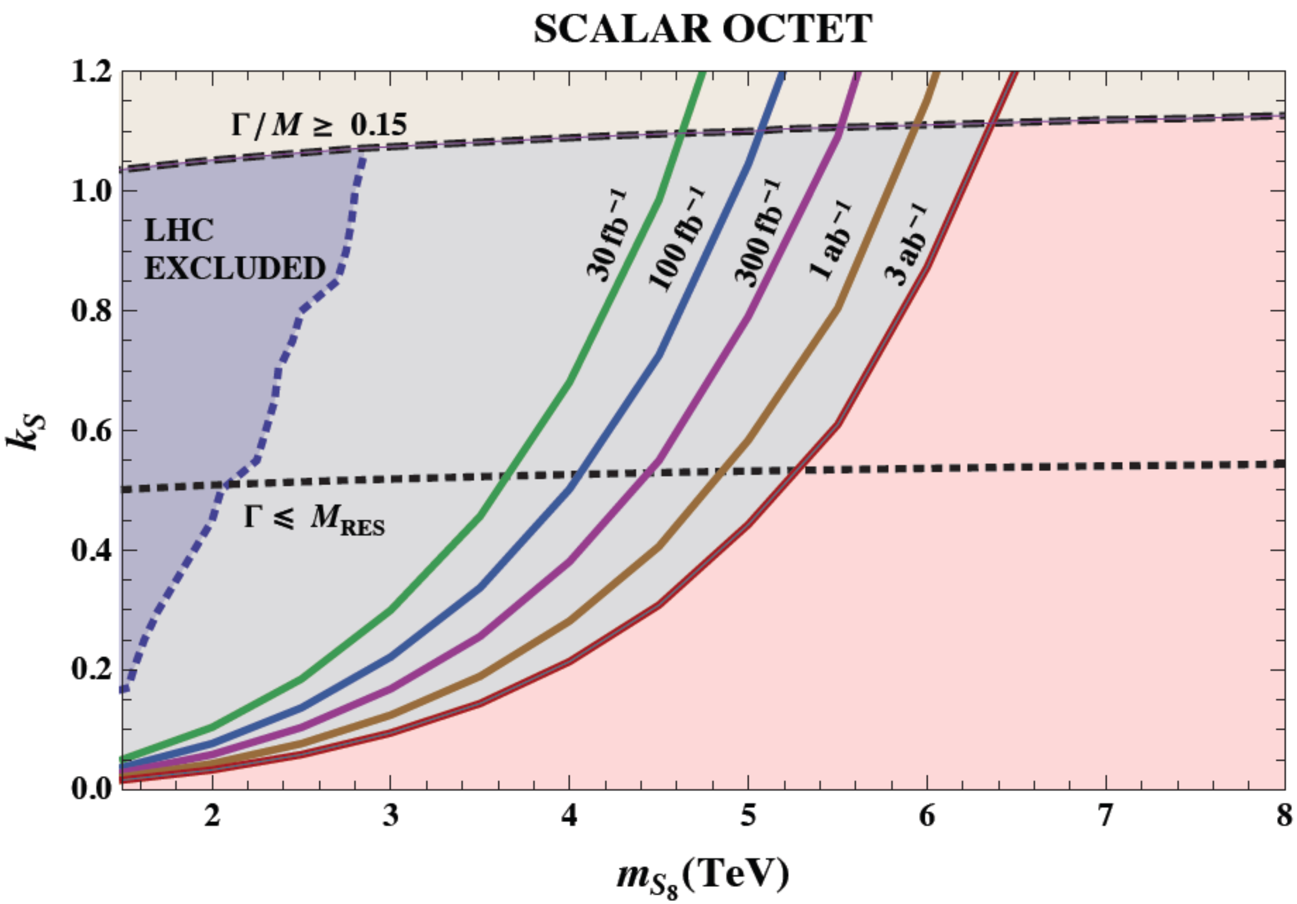
Discovery Region (FU Coloron)



Discovery Region (q*)



Discovery Region (scalar octet)



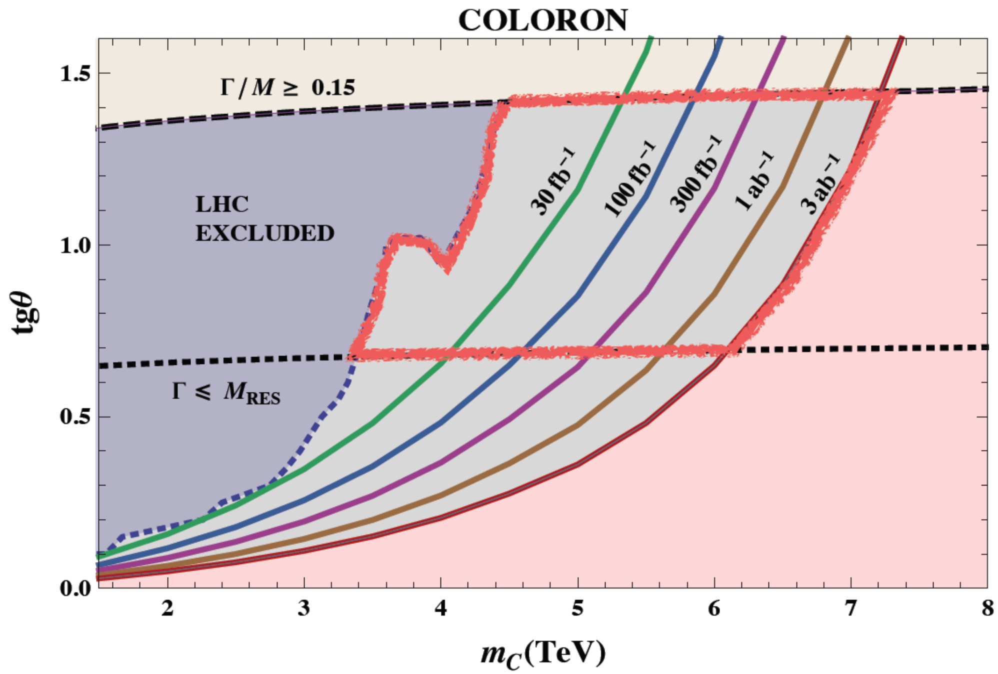
The Color Discriminant Variable

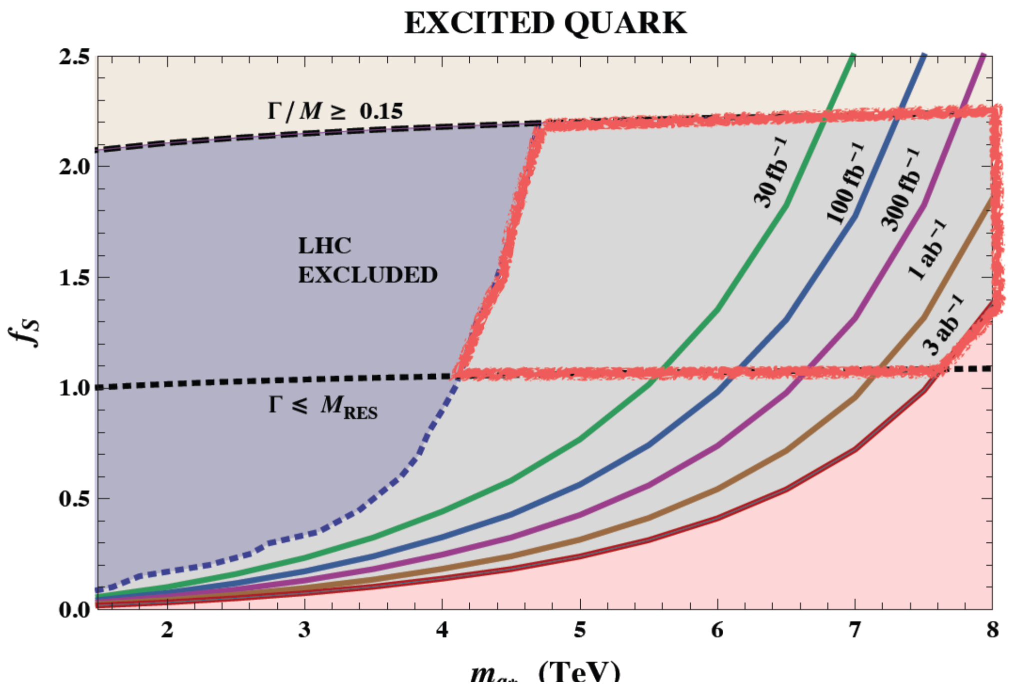
- Defined as

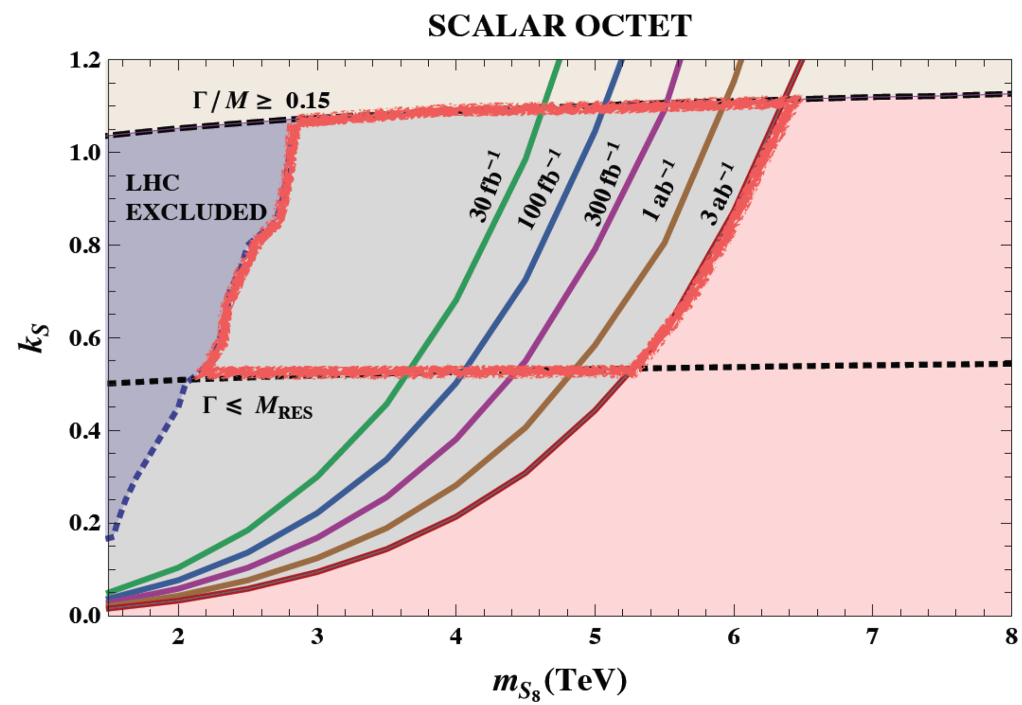
$$D_{col} = \frac{\sigma_{jj} M^3}{\Gamma}$$

Introduced in
Atre, Chivukula, Ittisamai, Simmons Phys. Rev. D 88, 055021 (2013)

- Dimension-less in the unit $\hbar = c = 1$
- Can be calculated at the LHC from the measurements of the di-jet signal cross section, the resonance mass and the resonance width.
- Dcol reflects the different color and Lorentz structures of the resonances and depends on the PDFs
- The dependence of Dcol on the di-jet mass is controlled by the PDFs

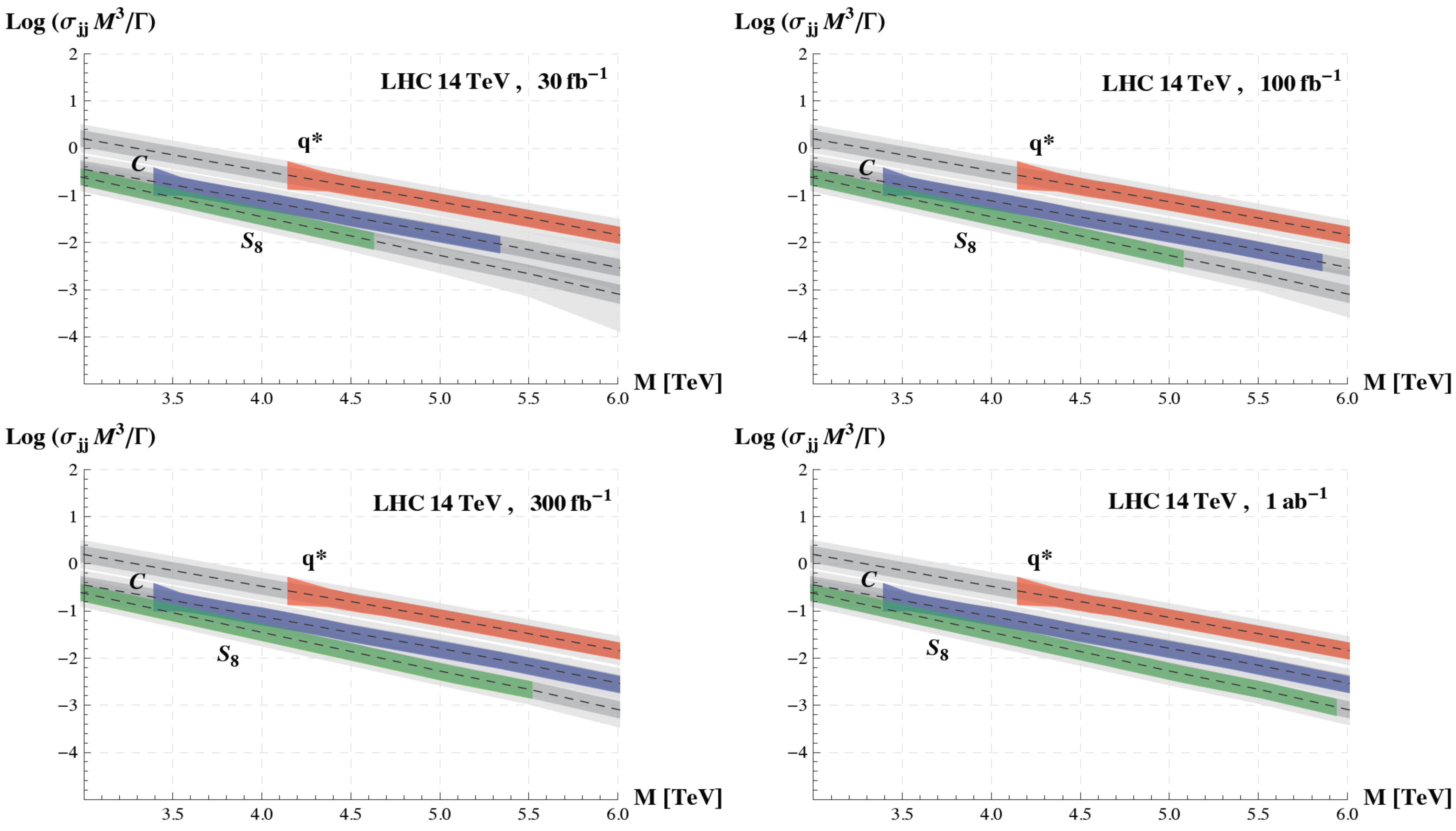


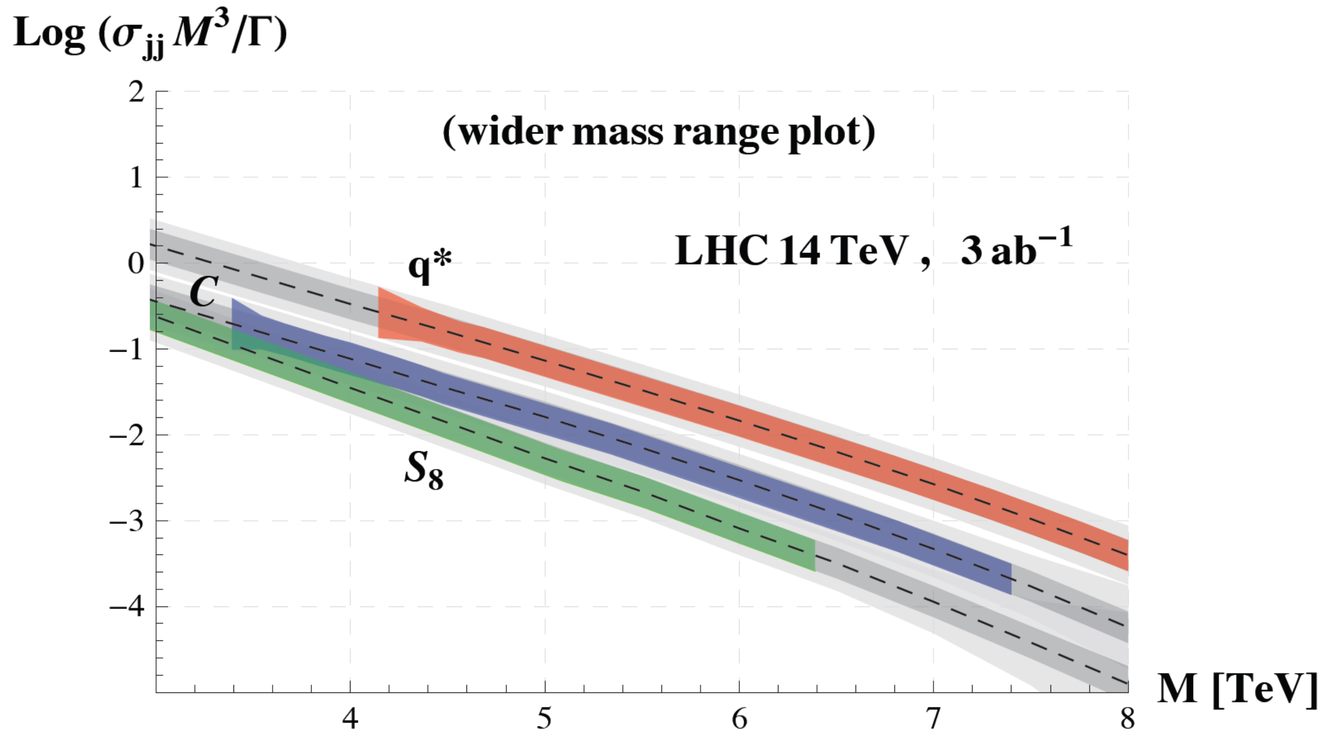




Marked region: LHC-14 can both DISCOVER the resonance and MEASURE Dcol

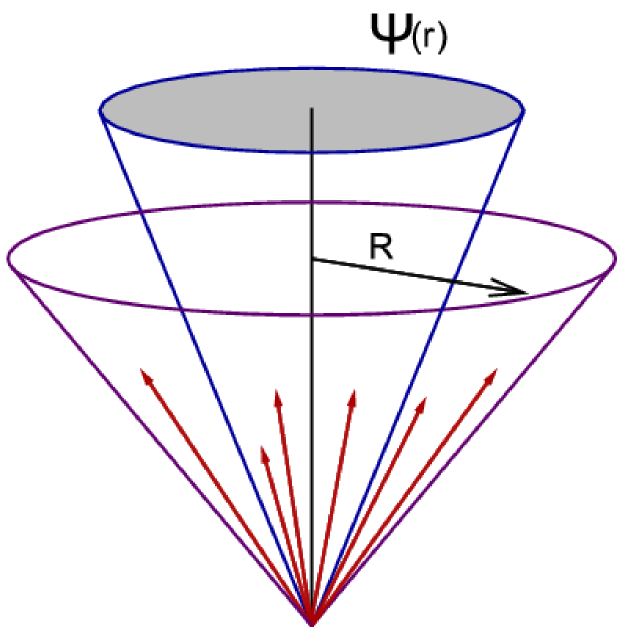
Dcol in the experimentally accessible region, including the statistical and systematic uncertainties (Largest uncertainty: systematic error on the width measurement)





We find that an excited quark resonance can be efficiently distinguished from either a coloron or a scalar octet resonance by the color discriminant variable at the 14 TeV LHC. Discriminating between colorons and scalar octets is more challenging but we find it should be possible to establish a 2-3 sigma separation in the mass range 4-6 TeV

Jet Energy Profile

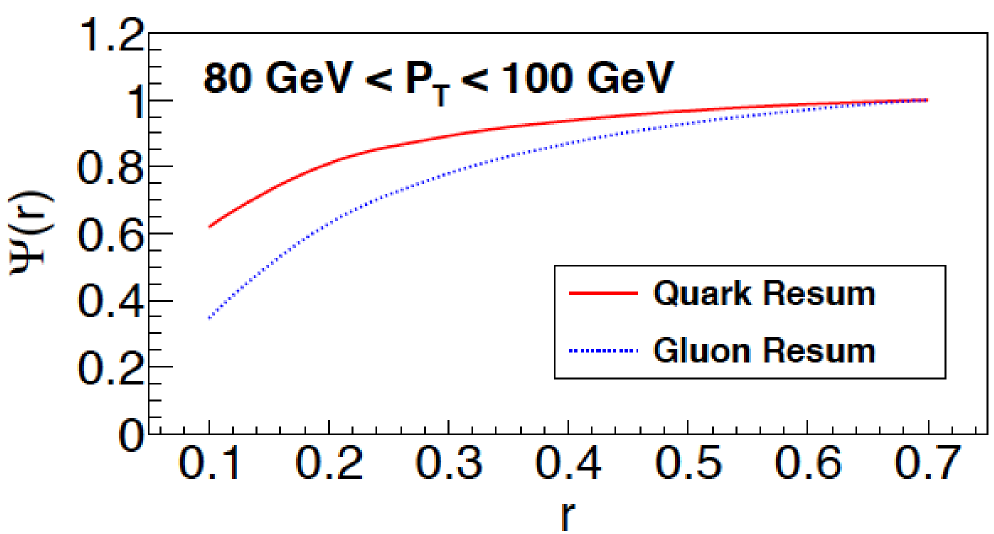


Average fraction of jet pT lying within a sub-cone of radius r

$$\psi(r) = \frac{1}{N_j} \sum_j \frac{p_T(0,r)}{p_T(0,R)}$$

Quarks C_F=4/3 Gluons: C_A=3

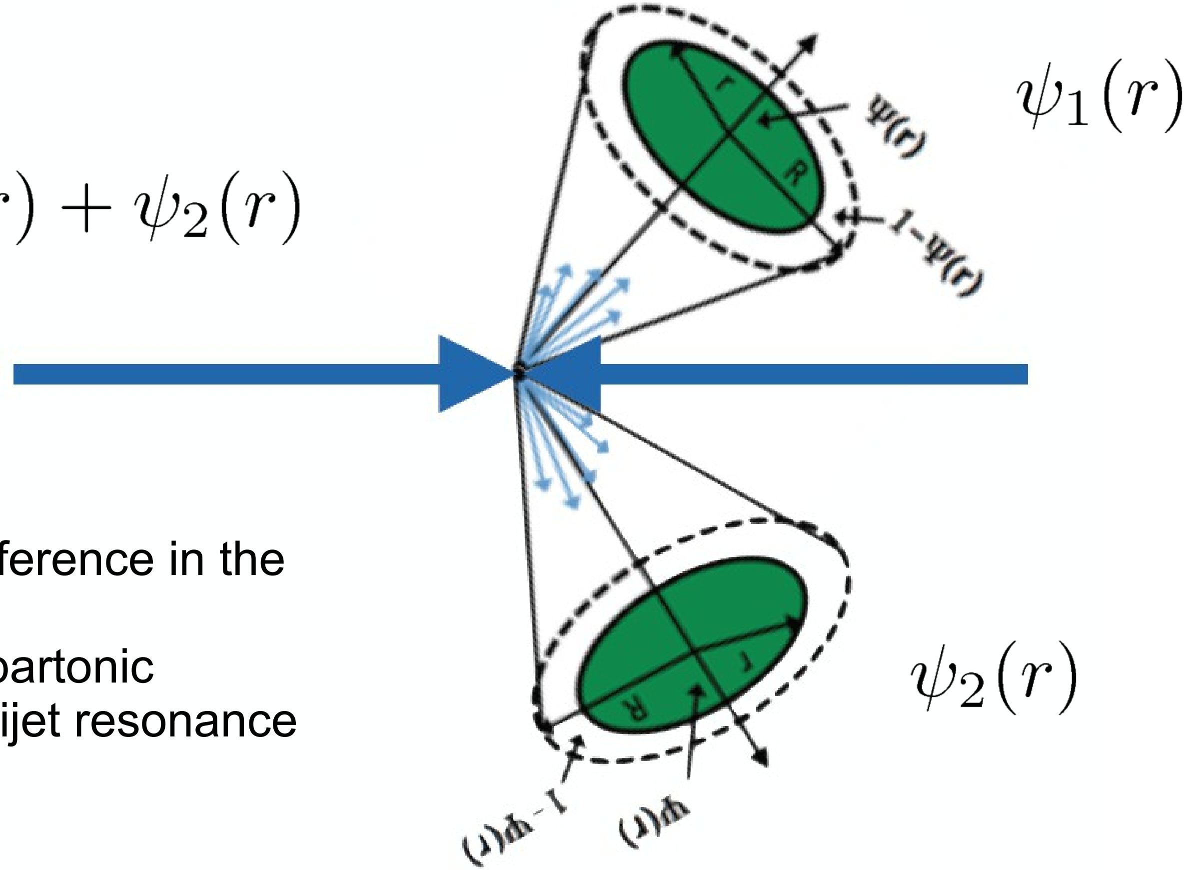
Gluon-jets irradiate more, slowly rising JEP
Quark-jets irradiate less, fast rising JEP



H. Li, Z. Li, C.-P. Yuan
PRD 87 (2013) 074025

Dijet energy profile

$$\psi_{jj}(r) = \psi_1(r) + \psi_2(r)$$



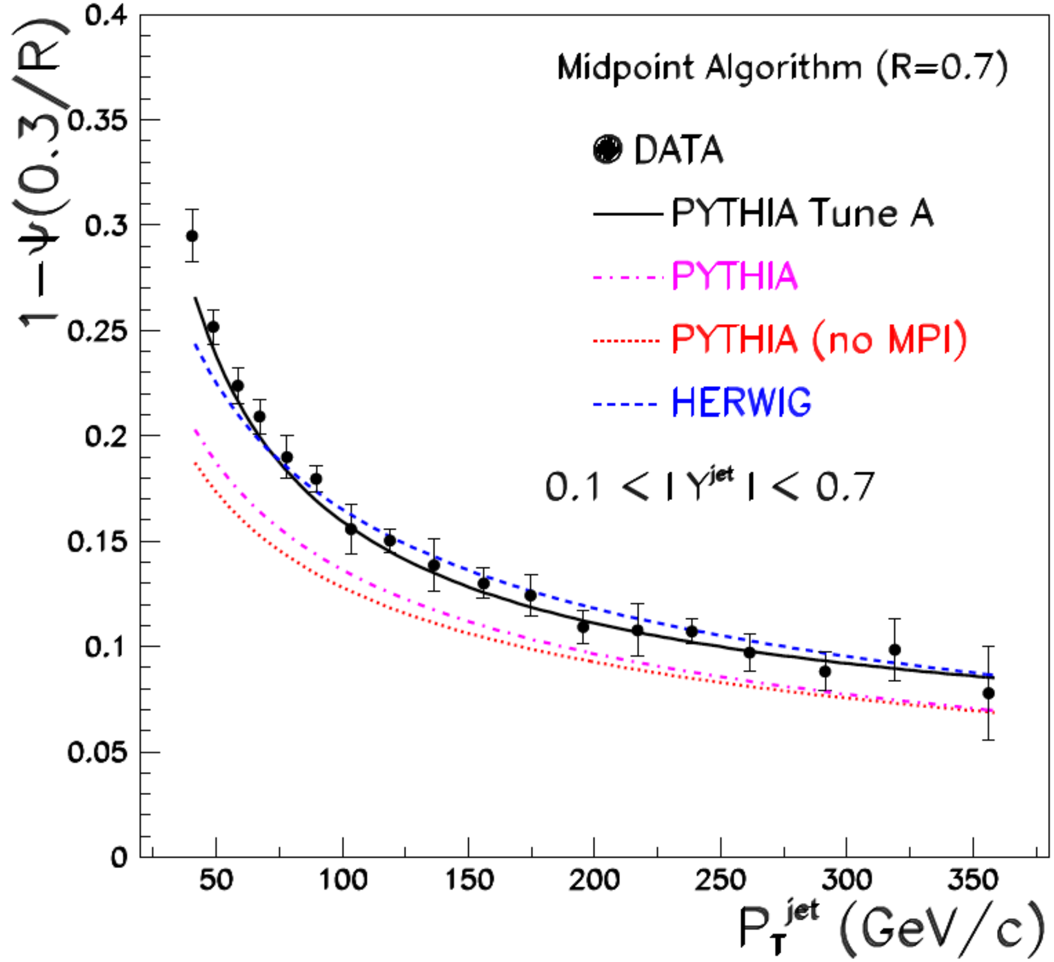
We will use the difference in the quark/gluon JEP
to distinguish the partonic composition of a dijet resonance

Similar technique recently applied to distinguish Higgs production mechanisms [Rentala *et al.* PRD88 (2013) 7, 073007] and Dark matter interactions [Agrawal, Rentala, JHEP 1405 (2014) 098]

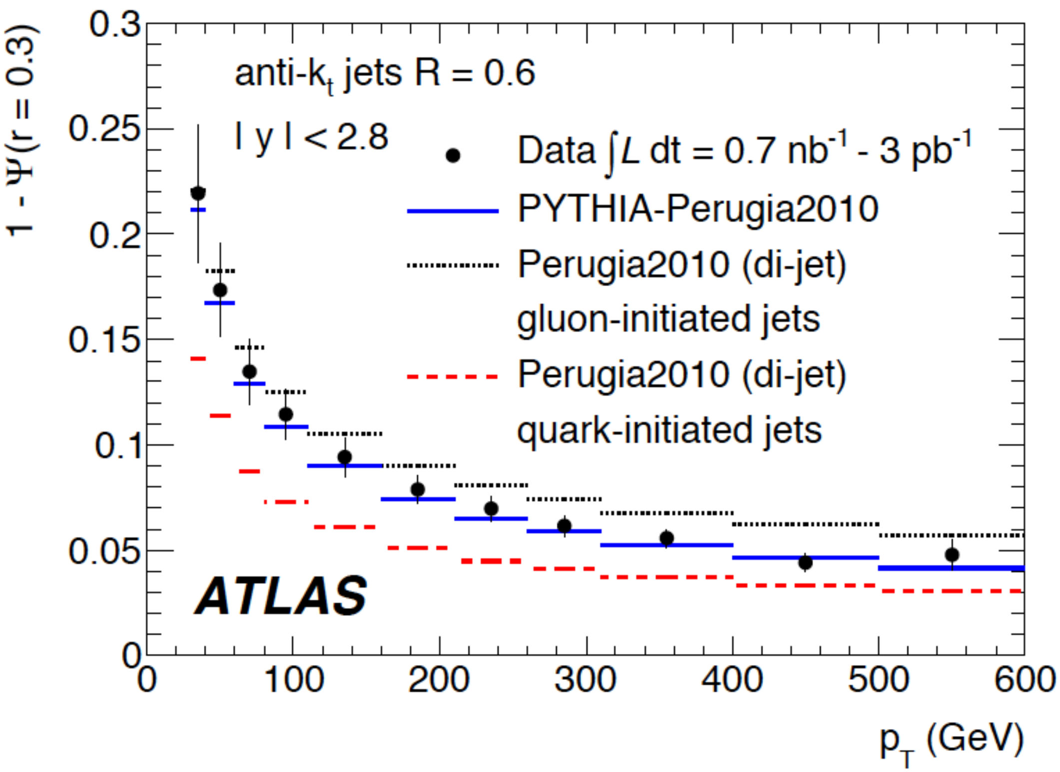
Study of jet shape in inclusive jet production

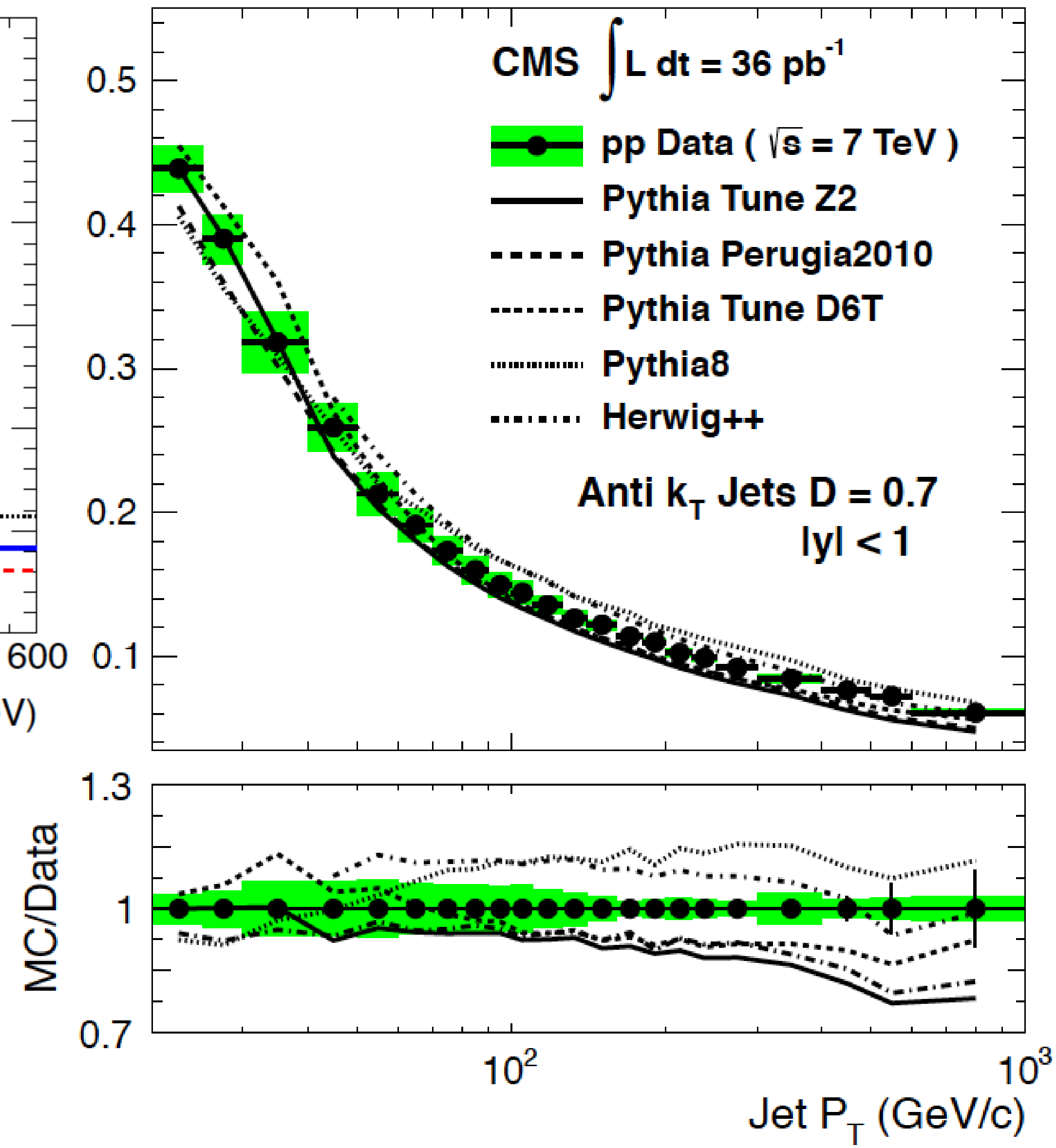
CDF 1.96 TeV

hep-ex/0505013
Phys.Rev. D71
(2005) 112002



LHC-7 measurements (inclusive jet production)

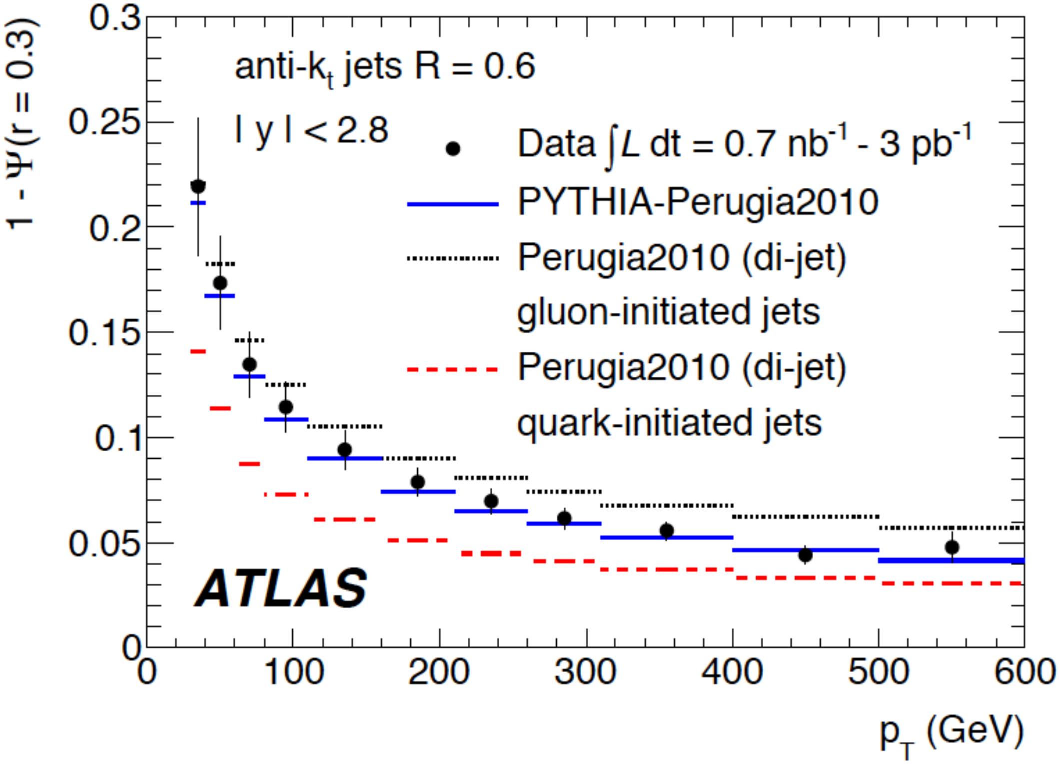


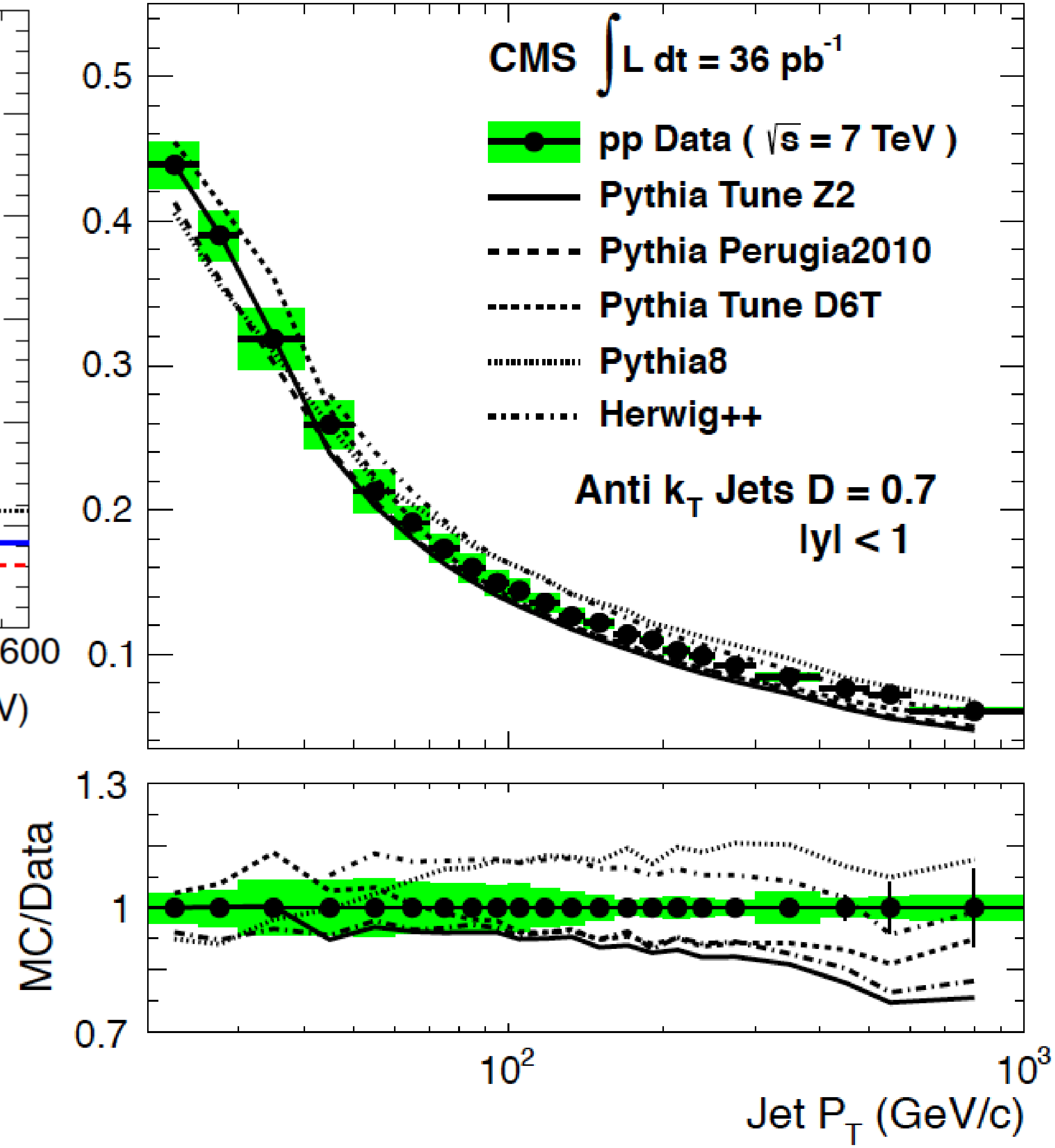


ATLAS, PRD 83 (2011) 052003

CMS, JHEP 1206 (2012) 160

LHC-7 measurements (inclusive jet production)





Tuning!

Data are well described by MC simulations.
But a tuning of the shower/hadronization parameters is needed

How to estimate the jet energy profile for dijet at LHC-14 ?

- By Monte Carlo simulation (example MG+Pythia or Herwig)

  but a tuning of MC parameters is needed (and we need LHC-14 data!)

- “Theoretically”. JEP can be calculated in perturbative QCD

Collins, Soper, Sterman, PRD 71 (2005) 112002
Li, Li, Yuan, PRL 107 (2011) 152001
PRD 87 (2013) 074025

- We will use *pQCD* calculations to estimate the *average* JEPs and *MC* simulations to evaluate, by means of pseudo-experiments, the *statistical uncertainty* on the JEP

“theoretical” evaluation of JEP

H.-N. Li, Z. Li, C.-P. Yuan, PRL 107 (2011) 152001; PRD 87 (2013) 074025

Nex-to-leading-logarithm resummation

(NLO calculations overshoot data)

Terms of the form $\alpha_S^n(\log(R/r))^{2n}$, $\alpha_S^n(\log(R/r))^{2n-1}$

are resummed to all order in α_s

$$\Psi(r) = \left[\sum_f \int \frac{dP_T}{P_T} \frac{d\hat{\sigma}_f}{dP_T} \bar{J}_f^E(1, P_T, \nu_{\text{fi}}^2, R, R)\right]^{-1} \sum_f \int \frac{dP_T}{P_T} \frac{d\hat{\sigma}_f}{dP_T} \bar{J}_f^E(1, P_T, \nu_{\text{fi}}^2, R, r)$$

Scale parameter which includes the effects of not-calculated sub-leading logarithms

“theoretical” evaluation of JEP

H.-N. Li, Z. Li, C.-P. Yuan, PRL 107 (2011) 152001; PRD 87 (2013) 074025

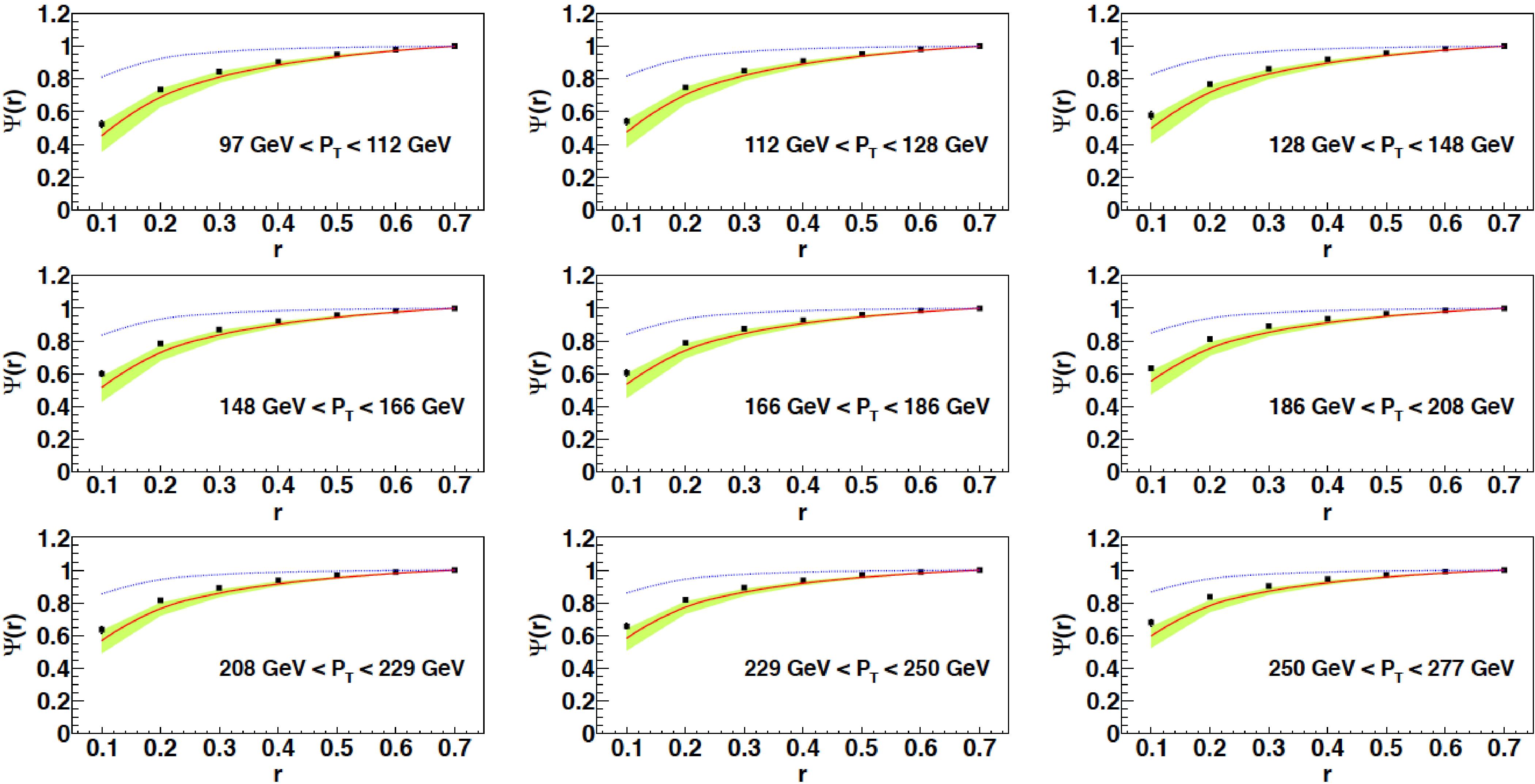
Nex-to-leading-logarithm resummation

Limitations of the pQCD prediction (small tuning also required in the theory prediction):
2 phenomenological parameters reflecting the theory uncertainty, which will need to be fixed once LHC data is available

our absolute results for the JEPs will not *precisely* match those to be expected at the LHC --- however, we expect the relative differences in the JEPs we find between the various kinds of resonances to be representative of what would be seen there.

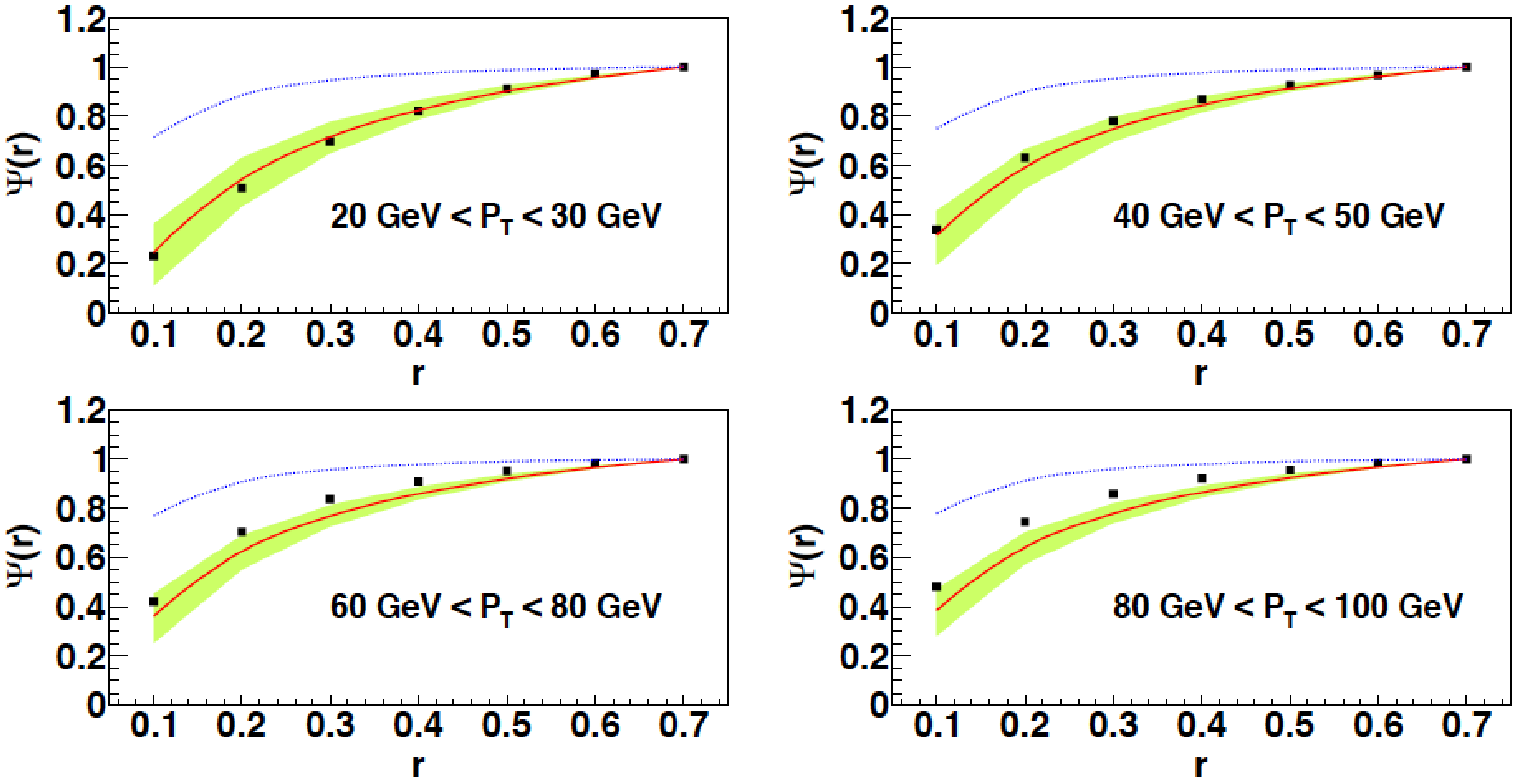
JEPs from Perturbative QCD Resummation vs CDF data

H.-N. Li, Z. Li, C.-P. Yuan, PRL 107 (2011) 152001; PRD 87 (2013) 074025



JEPs from Perturbative QCD Resummation vs CMS data

H.-N. Li, Z. Li, C.-P. Yuan, PRL 107 (2011) 152001; PRD 87 (2013) 074025



Theory uncertainty removable by calibration with data

Procedure (SIGNAL)

- We consider first the signal of a 4 TeV di-jet resonance, coming from an S8, C or q*, which can be discovered with approximately 30 fb-1 at the 14 TeV LHC and which has not been excluded by the present LHC-8 searches.
- We apply the CMS selection and we restrict to the dijet mass region

$$|M_{jj} - M| < \Gamma/2$$

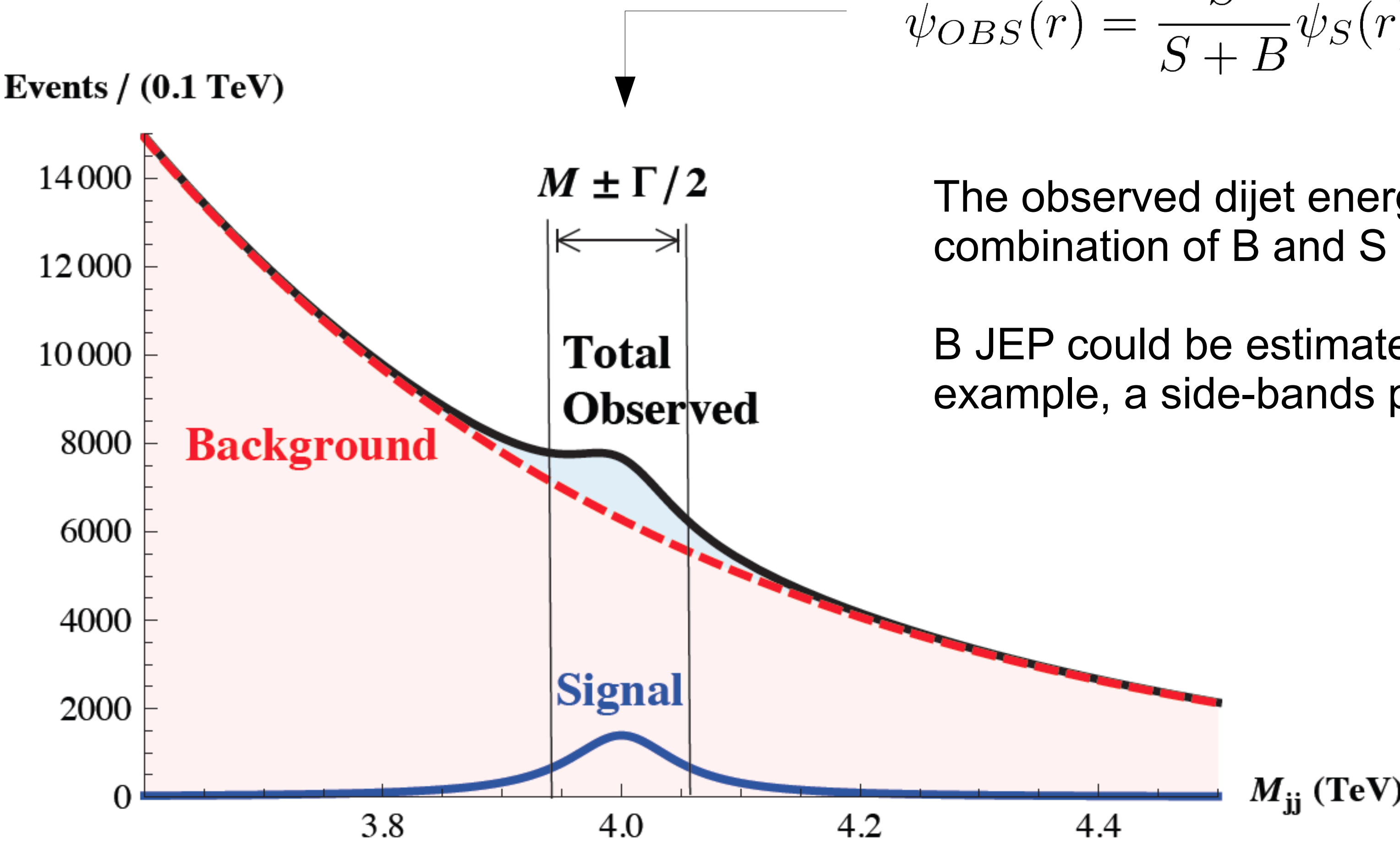
- We evaluate, in this kinematic region, the average JEP by pQCD calculation (we convolve the jet 4-momenta with the analytic jet functions)
- We obtain the statistical fluctuation on the JEP by running several MC simulations (MG5+Pythia; jets are clustered with Fastjet: anti-kt with R=0.5)

We find that the statistical uncertainty is Gaussian (Poisson errors)

$$(\delta\psi_S(r))^2 \approx \frac{\sigma^2(r)}{S}$$

Background subtraction

$$\psi_{OBS}(r) = \frac{S}{S+B}\psi_S(r) + \frac{B}{S+B}\psi_B(r)$$



The observed dijet energy profile is a combination of B and S profiles

B JEP could be estimated through, for example, a side-bands procedure

Even if it is possible to subtract the B profile, the statistical uncertainty on B affects the measurement of the S JEP

Background subtraction

$$\psi_S(r) = \psi_{OBS}(r) + \frac{B}{S}(\psi_{OBS}(r) - \psi_B(r))$$

For the signal we have found $$(\delta\psi_S(r))^2 \approx \frac{\sigma^2(r)}{S}$$

We make the reasonable assumption of same σ "per event" statistical error for S and B:

$$(\delta\psi_{OBS}(r))^2 \approx \frac{\sigma^2(r)}{S+B} \qquad (\delta\psi_B(r))^2 \approx \frac{\sigma^2(r)}{B} \ .$$

$$(\delta\psi_S)^2 \approx \underbrace{\frac{\sigma^2}{S}\left[1 + 2\frac{B}{S}\right]}_{\text{``dilution" in the measurement of S JEP due to QCD background}} + \underbrace{\frac{(\psi_S - \psi_B)^2}{S}}_{\text{From the uncertainty on S (number of signal events)}}$$

Background subtraction

$$\psi_S(r) = \psi_{OBS}(r) + \frac{B}{S}(\psi_{OBS}(r) - \psi_B(r))$$

For the signal we have found $$(\delta\psi_S(r))^2 \approx \frac{\sigma^2(r)}{S}$$

We make the reasonable assumption of same σ "per event" statistical error for S and B:

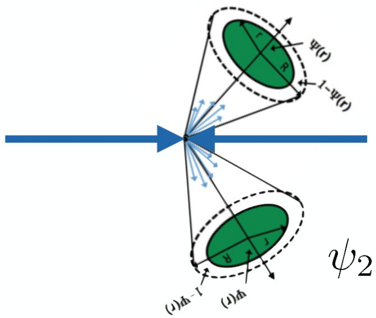
$$(\delta\psi_{OBS}(r))^2 \approx \frac{\sigma^2(r)}{S+B} \qquad (\delta\psi_B(r))^2 \approx \frac{\sigma^2(r)}{B} \; .$$

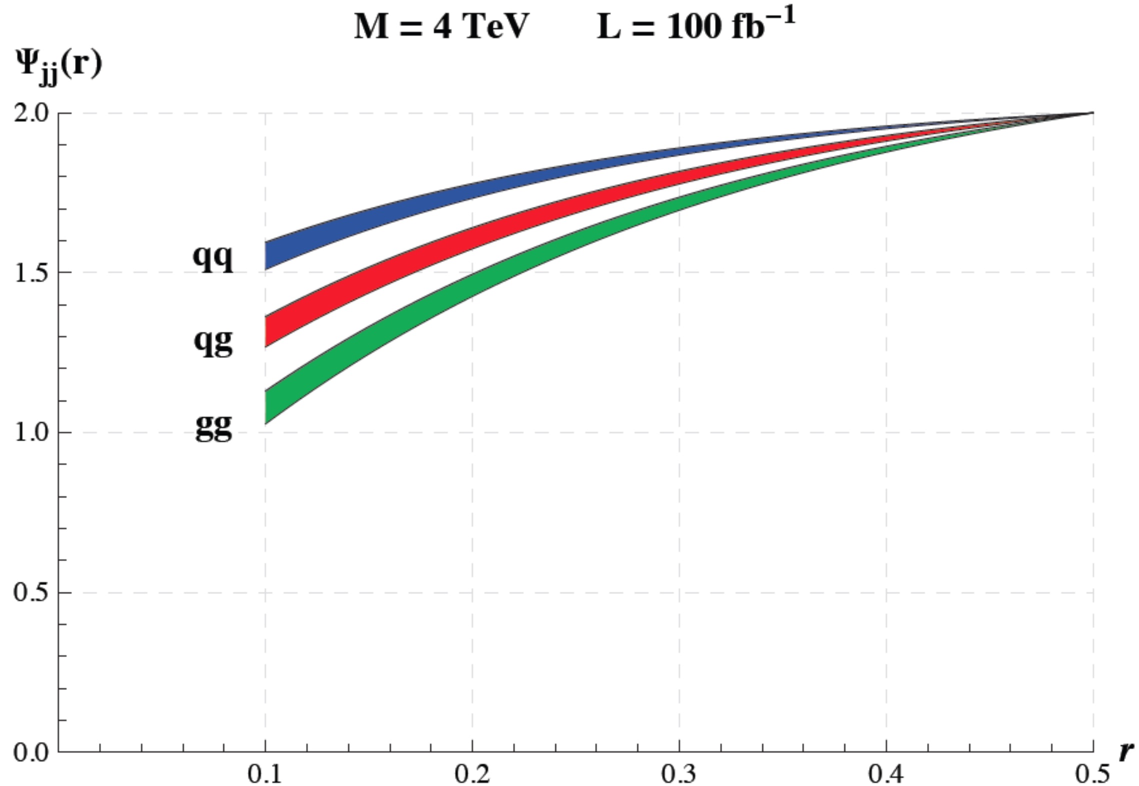
$$(\delta\psi_S)^2 \approx \boxed{\frac{\sigma^2}{S}\left[1 + 2\frac{B}{S}\right]} + \frac{(\psi_S - \psi_B)^2}{S}$$

Larger term; because B/S is large in the relevant param space

Results (4 tev)

$$\psi_{jj}(r) = \psi_1(r) + \psi_2(r)$$





Resonance mass: 4 TeV
Benchmark couplings: (C) tanθ=0.6 , (q*) f_S=0.4 , (S_8) k_S=0.65

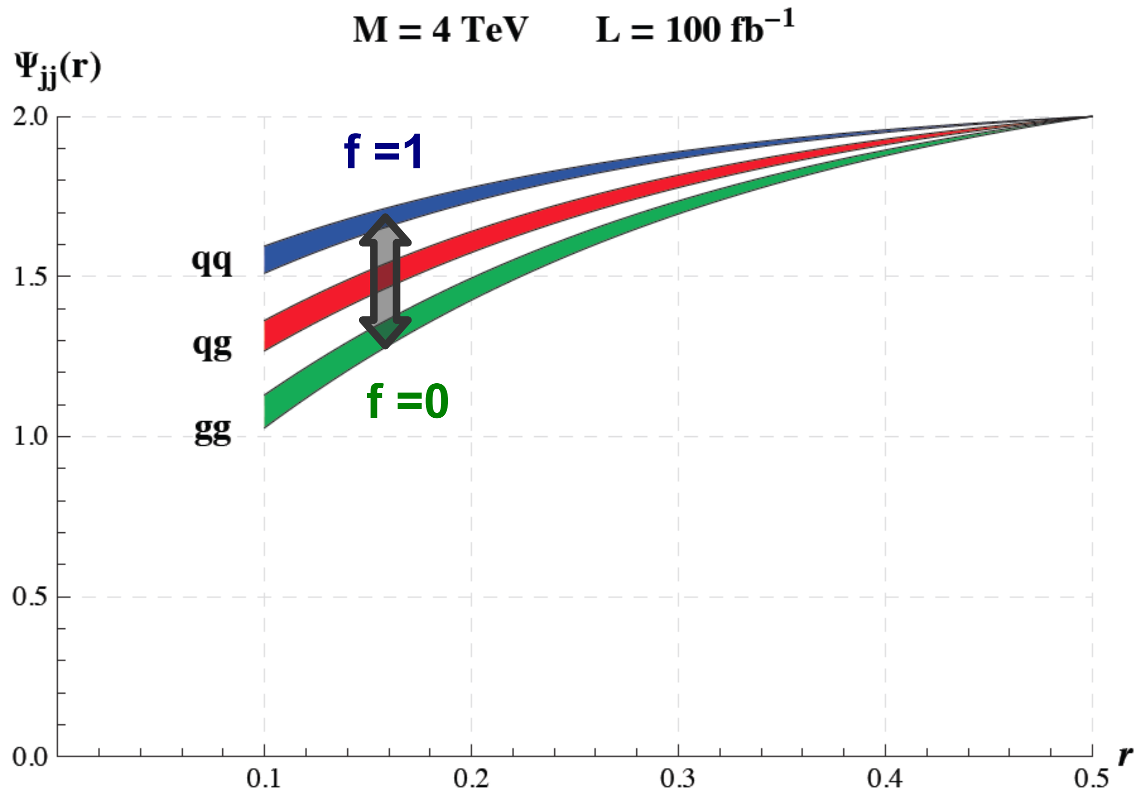
f parameter

we can parameterize a generic dijet profile of the signal as

$$\psi_S(r) = f\psi_{\bar{q}q}(r) + (1-f)\psi_{gg}(r)$$

Fit-parameter f indicates the fraction of quark-jets in a generic di-jet resonance

$$\begin{cases} f=1 \ \ (qq) \quad C \\ f=0.5 \ \ (qg) \quad q^* \\ f=0 \ \ (gg) \quad S_8 \end{cases}$$



f parameter

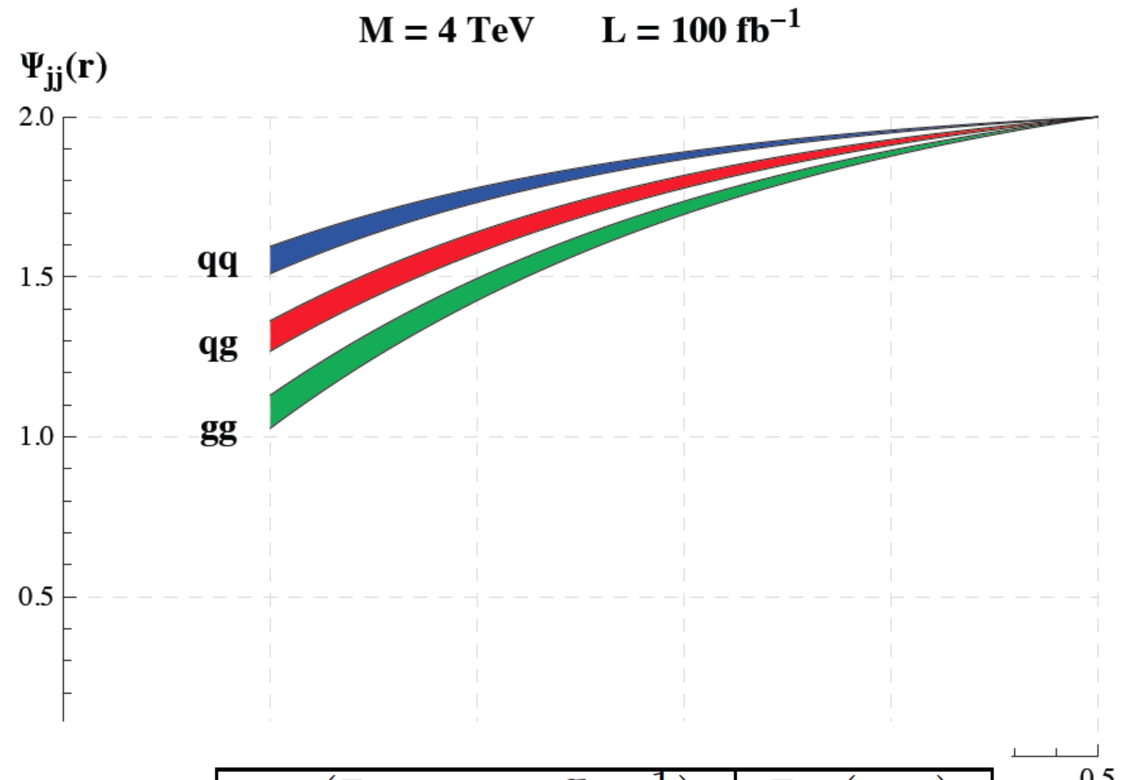
We translate the error on the JEP into an error on f

	f
$\bar{q}q$	1.00 ± 0.06
qg	0.50 ± 0.07
gg	0.00 ± 0.08

$$\sigma(\bar{q}q - gg) = \frac{\bar{f}_{\bar{q}q} - \bar{f}_{gg}}{\sqrt{\sigma^2(f_{\bar{q}q}) + \sigma^2(f_{gg})}}$$

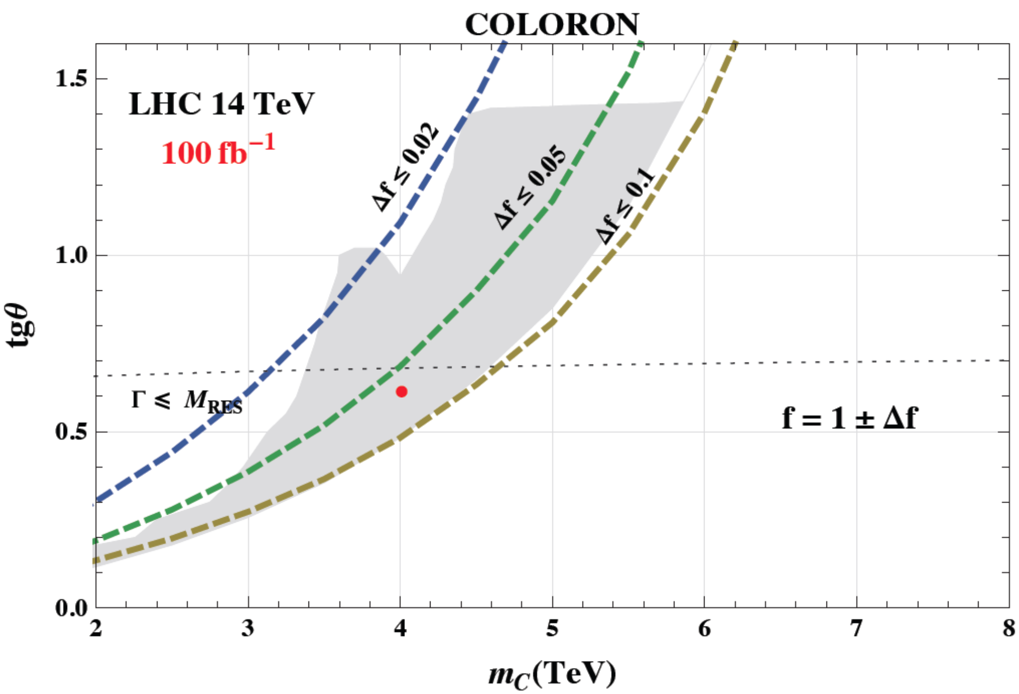
$$\sigma(\bar{q}q - qg) = \frac{\bar{f}_{\bar{q}q} - \bar{f}_{qg}}{\sqrt{\sigma^2(f_{\bar{q}q}) + \sigma^2(f_{qg})}}$$

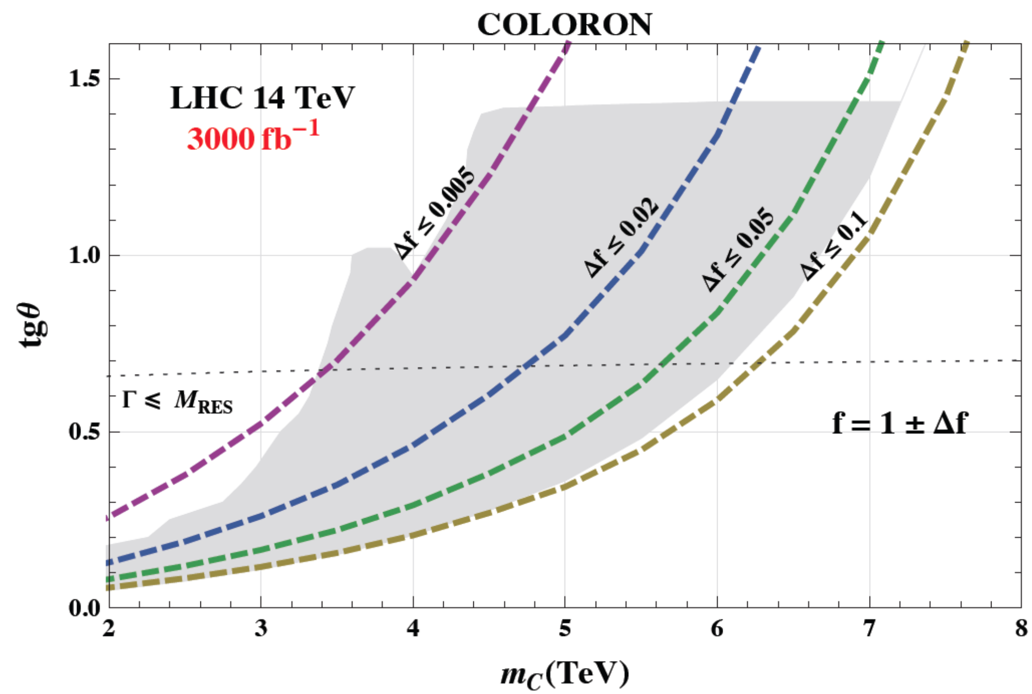
$$\sigma(qg - gg) = \frac{\bar{f}_{qg} - \bar{f}_{gg}}{\sqrt{\sigma^2(f_{qg}) + \sigma^2(f_{gg})}}$$



	σ (L=100 fb^{-1})	L (5σ)
$\bar{q}q$ - qg	5.4	85
qg - gg	4.7	110
$\bar{q}q$ - gg	10	25

Statistical uncertainty in the discovery region





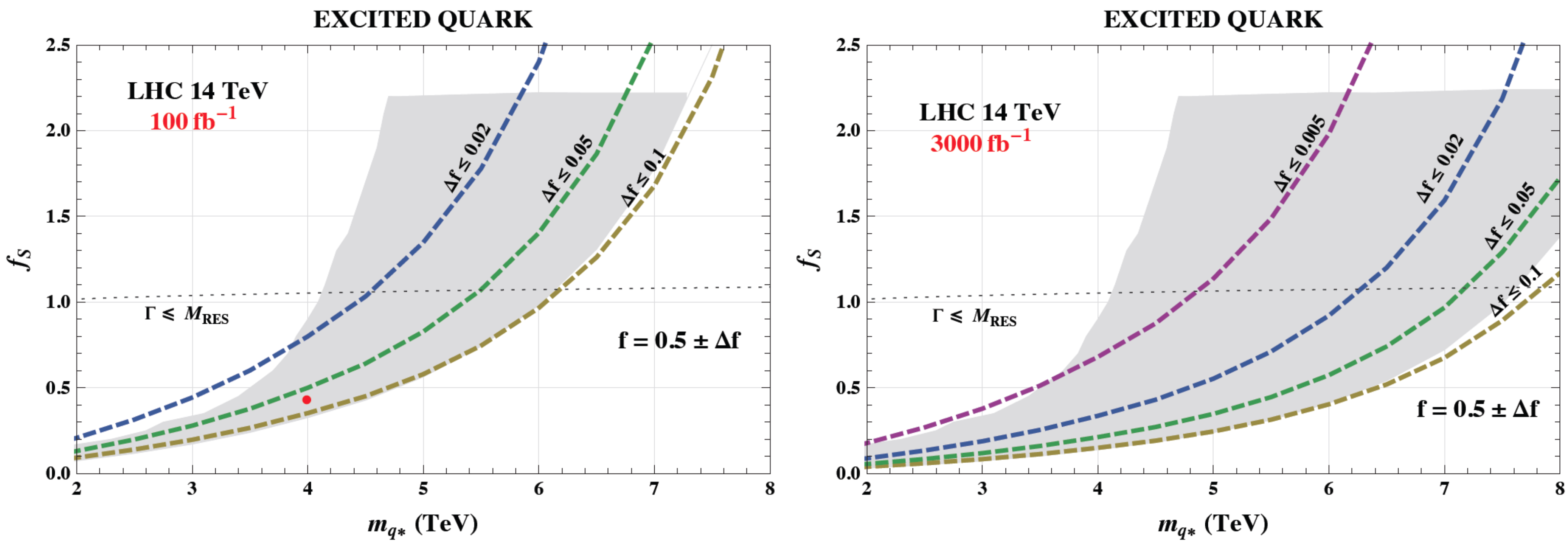
f =1 (qq) C

f =0.5 (qg) q*

f =0 (gg) S_8

$\Delta f \leq 0.1$ → 5-sigma separation from the other resonances

Statistical uncertainty in the discovery region



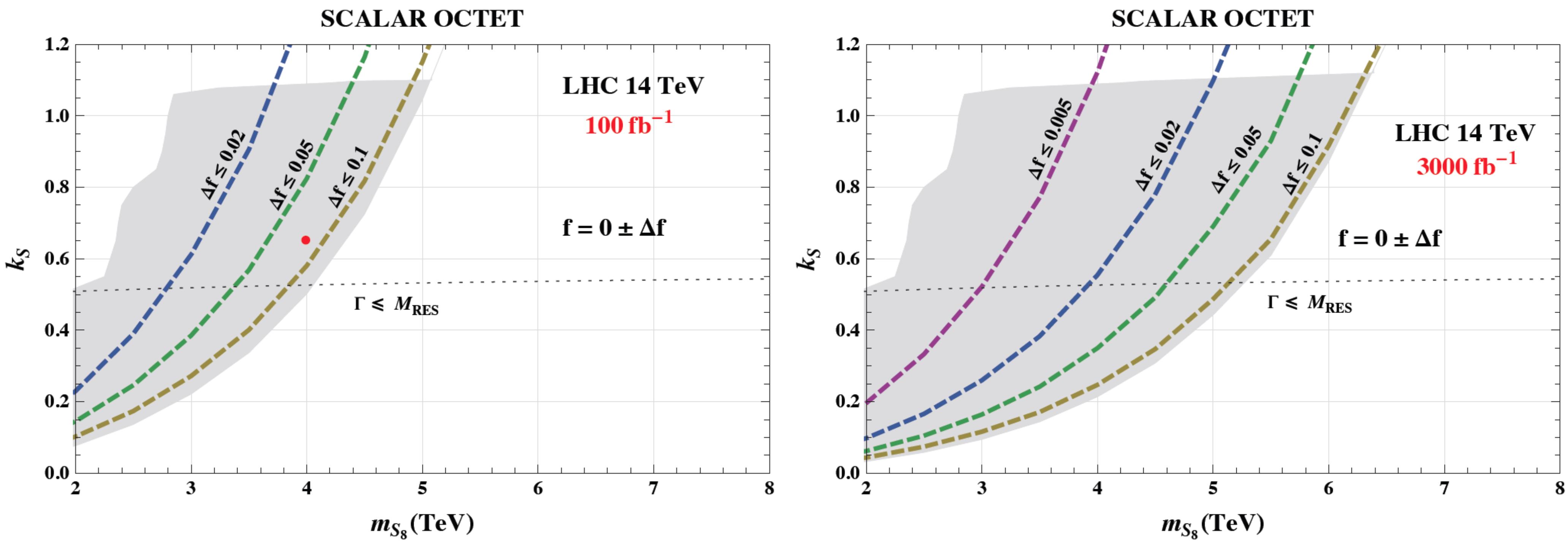
f =1 (qq) C

f =0.5 (qg) q*

f =0 (gg) S_8

$\Delta f \leq 0.1$ → 5-sigma separation from the other resonances

Statistical uncertainty in the discovery region



f =1 (qq) C

f =0.5 (qg) q*

f =0 (gg) S_8

Large **statistic** separation among the three types of resonances in essentially the entire relevant parameter space where we can reach a 5-sigma discovery at the 14 TeV LHC.

Conclusions

Two different strategies to reveal the nature of a di-jet resonance at the 14 TeV LHC:

Dcol (which can be constructed from the measurements in the dijet channel of the signal cross section and of the resonance mass and width) can cleanly distinguish (including both statistic and systematic uncertainties) a qg excited quark from either a q-qbar coloron or a gg color-octet scalar. A 2-3 sigma separation between colorons and color-octet scalars is also possible for masses of 4-6 TeV

<u>Limitations</u>:

Model-dependent

Cannot be used in the very narrow regime (Γ< Mres)

Conclusions

Two different strategies to reveal the nature of a di-jet resonance at the 14 TeV LHC:

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Analysis of **diJet Energy Profile** can distinguish (in a model-independent way) gg, qg and qq resonances, after accounting for statistical uncertainties in the signal and the background.

Can be applied even in the very narrow regime (Γ< Mres)

Conclusions

Two different strategies to reveal the nature of a di-jet resonance at the 14 TeV LHC:

Dcol (which can be constructed from the measurements in the dijet channel of the signal cross section and of the resonance mass and width) can cleanly distinguish (including both statistic and systematic uncertainties) a qg excited quark from either a q-qbar coloron or a gg color-octet scalar. A 2-3 sigma separation between colorons and color-octet scalars is also possible for masses of 4-6 TeV

Analysis of **diJet Energy Profile** can distinguish (in a model-independent way) gg, qg and qq resonances, after accounting for statistical uncertainties in the signal and the background.

We have not tried to evaluate systematic uncertainties. This can be done (better by experimentalists) through detailed detector study once sufficient 14 TeV dijet data is in hand.

Systematics on JEP

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at very large p_T where the measurements are still statistically limited. In the case of the integrated measurements, the total systematic uncertainty varies between 10% and 2% (4% and 1%) at $r = 0.1$ ($r = 0.3$) as p_T increases, and vanishes as r approaches the edge of the jet cone.

Systematic uncertainties at the 1 percent level for pT~ 600 GeV

Uncertainties on D_{col}

$$\left(\frac{\Delta D}{D}\right)^2 = \left(\frac{\Delta \sigma_{jj}}{\sigma_{jj}}\right)^2 + \left(3\frac{\Delta M}{M}\right)^2 + \left(\frac{\Delta \Gamma}{\Gamma}\right)^2$$

$$\left(\frac{\Delta \sigma_{jj}}{\sigma_{jj}}\right)^2 = \frac{1}{N} + \epsilon^2_{\sigma SYS}$$

$$\left(\frac{\Delta M}{M}\right)^2 = \frac{1}{N}\left[\left(\frac{\sigma_\Gamma}{M}\right)^2 + \left(\frac{M_{res}}{M}\right)^2\right] + \left(\frac{\Delta M_{JES}}{M}\right)^2$$

$$\left(\frac{\Delta \Gamma}{\Gamma}\right)^2 = \frac{1}{2(N-1)}\left[1 + \left(\frac{M_{res}}{\sigma_\Gamma}\right)^2\right]^2 + \left(\frac{M_{res}}{\sigma_\Gamma}\right)^4 \left(\frac{\Delta M_{res}}{M_{res}}\right)^2$$

$\epsilon_{\sigma SYS} = 0.41$ (14 TeV LHC [45]) $\quad M_{res}/M = 0.035$ (8 TeV CMS [2])

$\Delta M_{res}/M_{res} = 0.1$ (8 TeV CMS [3]) $\quad (\Delta M_{JES}/M) = 0.013$ (8 TeV CMS [3])

[45] CERN-CMS-NOTE-2006-070 [2] CMS PAS-EXO-12-059
[3] CMS arXiv: 1302.4794